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IIT RESEARCH INSTITUTE
Technology Center
Chicago, Illinois 60616

IITRI Project J6107

Final Report

SUMMARY

FRAGMENTATION OF REINFORCED CONCRETE SLABS

Subcontract B-70942(4949A-34)-US
OCD Work Unit 3322B

by

Ralph L. Barnett
Paul C. Hermann

for

Office of Civil Defense
Office of the Secretary of the Army
Washington, D. C. 20310

OCD Review Notice

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October 1968

SUMMARY

FRAGMENTATION OF REINFORCED CONCRETE SLABS

This report presents the results of an investigation of the debris producing characteristics of reinforced concrete wall, floor and roof panels. The principal conclusion of this study is that reinforced concrete (R/C) slabs do not constitute a significant source of debris.

It is convenient for analysis to identify two types of fragments. The first, called primary fragments, are caused by structural action such as bending and membrane tension. These pieces are prismatic with two sides formed by the top and bottom slab faces. All other fragments are called secondary; secondary fragments may be quite irregular in shape and are caused by, for example, stress waves or shear stresses at the steel/concrete interfaces. For primary fragments to occur, all of the reinforcing steel around their edges must be fractured, whereas secondary fragments can and normally do arise without such fracturing of the steel reinforcement.

The first consideration in the study was the loading anticipated on R/C slabs. When used above grade, R/C slabs are most frequently used as floor or roof panels. The horizontal orientation for these applications precludes the development of significant net transverse loads in the Mach region created by a nuclear detonation. Large transverse loads are found in ceiling slabs which cover basements or in roof and floor slabs exposed to high altitude bursts. In these circumstances the tenacity of R/C slabs operates to minimize their total loading. Initial cracking or breaching of the slabs allows the overpressure to build up on the downstream side. This diminishes the net transverse loading which in turn reduces the severity of the post cracking behavior.

A second consideration of this study was the transport of R/C fragments which might be formed. The downward pressures acting on basement ceiling slabs or roof and floor slabs exposed to high altitude bursts produce a downward velocity that tends to restrict any fragments to the vicinity of their parent structures. If large concrete fragments were to form, both field data and theoretical predictions indicate that they would be transported only short distances from their initial locations. No tendency to form small primary fragments was observed. Secondary fragments can be produced which will have significant horizontal displacement; however, they are formed under large net transverse forces whose conditions do not favor horizontal transport. The amount and size of secondary fragments is small and would not contribute significantly to street congestion, but would be significant in evaluating personnel vulnerability.

The third area of study on this program was the actual fragment formation of R/C panels. Simply supported one-way and two-way slabs can be distorted enough to allow them to push through their supports. Under these conditions they will remain intact and form one large primary fragment. Also, whenever the slab dimensions make it stronger in bending than in shear, it is possible to produce forces of sufficiently large magnitude to cause an entire slab to punch out by shearing along its periphery. In either case, such large fragments would fall to the ground long before any reasonable horizontal motion could be imparted to them.

In all the cases observed, secondary fragments took the form of chips and chunks of concrete broken off of the tension face of the slab below the tension steel. This layer of concrete is usually only 0.75 in. in thickness - the minimum cover specified by the ACI code. The concrete above the tension steel remains intact. The splitting cracks, caused by wedging of the

deformed reinforcing bars, occur over the rods on the tension face. This feature limits the maximum size of a secondary fragment to that of a 0.75 in. plate with the dimensions of the reinforcing grid.

The conclusion of this study is that R/C slabs do not contribute significantly to debris accumulation. This conclusion was unforeseen at the start of the program which was in fact directed at predicting the amount of debris accumulated from R/C panels. The justification both analytical and experimental for this unexpected conclusion, is contained in this final report.

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FRAGMENTATION OF REINFORCED CONCRETE SLABS

ABSTRACT

A reexamination of the blast effects literature from the point of view of fragmentation leads to the conclusion that reinforced concrete slabs do not constitute a significant source of debris in the postattack environment. Both the initial orientation and the self-adjusting geometry of slabs minimize their transverse loading. Also, the horizontal displacement of potential slab fragments tends to be small because of their high ballistic coefficients and/or high downward acting loading. Finally, the steel reinforcing bars tenaciously tie the various pieces of fractured slab to the supports and to each other even at pressure levels as high as 100 psi.

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CHAPTER I

INTRODUCTION AND CONCLUSIONS

One of the central problems in a nuclear postattack environment is the reestablishment of vital transportation links. Many requirements must be fulfilled in reaching this goal; but, few are as impressive as the removal of debris accumulations from important streets and arteries. To perform this task with the efficiency and dispatch demanded in emergency situations, planning must embrace the full scope of considerations involving attack prediction, target description, fragment generation, particle transport, and debris accumulation. This report represents only a small assignment in this overall picture. Specifically, it investigates the fragmentation of reinforced concrete slabs.

The principal conclusion of our study is that reinforced concrete (R/C) slabs do not constitute a significant source of debris. This result is based on three major observations that are developed in the text. Before summarizing these findings we shall identify two types of fragments which can be generated from a slab. The first are called primary fragments and they are caused by structural action such as bending and membrane tension. These pieces are prismatic with two sides formed by the top and bottom slab faces. They are of the type that might be formed by a giant cookie cutter being pressed into the slab face. All other fragments will be called secondary fragments; they may be quite irregular in shape and they may be caused by, for example, stress waves or shear stresses at the steel/concrete interfaces. We note that primary fragments require that all of the reinforcing steel around their edges be fractured; secondary fragments can arise without fracturing steel.

The first of our three major observations deals with the loading of R/C slabs. When these structures are used above grade, they are most often employed as floor or roof elements.

Their horizontal orientation precludes the development of significant net transverse loads in the Mach region created by a nuclear detonation. Large transverse loads are found in ceiling slabs which cover basements or in roof and floor slabs exposed to high altitude bursts. In these circumstances the tenacity of R/C slabs operates to minimize their total loading. Initial cracks or breaches in the slabs allow the overpressure to build up on the downstream side. This diminishes the net transverse loading which in turn reduces the severity of the post cracking behavior. Cases are described in the text in which slabs with fixed supports are broken into petals which rotate about the fixed edges to minimize the area exposed to the dynamic pressure in much the same manner as a weather vane.

Our second group of observations concern the transport of slab fragments. To begin with, the downward pressures acting on basement ceiling slabs or roof and floor slabs exposed to high altitude bursts produce a corresponding downward velocity that tends to restrict any fragments to the vicinity of their parent structures. If large concrete fragments were to form, both field data and theoretical predictions indicate that they would be transported only short distances from their initial locations. No tendency to form small primary fragments was observed. Secondary fragments can be produced whose ballistic coefficients* are sufficiently small to cause significant horizontal displacement; however, they are formed under large net transverse forces whose conditions do not favor horizontal transport. Furthermore, the amount and size of secondary fragments is small and would not contribute in a real way to street congestion. Their significance is in the area of personnel vulnerability.

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*Ballistic Coefficient = weight/(drag coefficient) (projected area)

We have indicated that the loading and transport characteristics of R/C slabs conspire to minimize fragment formation and horizontal displacement. Our final observations deal with the actual fragmentation resistance of these elements. It is reasonably clear that simply supported one-way and two-way slabs can be distorted enough to allow them to push through their supports. Under these conditions they will remain intact and form one large primary fragment. Also, whenever the slab dimensions make it stronger in bending than in shear, it is possible to produce forces of sufficiently large magnitude to cause an entire slab to punch out by vertical shearing along its periphery. In either case, such large fragments would fall to the ground long before any reasonable horizontal motion could be imparted to them. No examples could be found where primary fragments were formed; loadings as high as 120 psi were examined. Only in rare and extreme circumstances were steel fractures even obtained.

In all the cases observed, secondary fragments took the form of chips and chunks of concrete broken off of the tension face of the slab below the tension steel. This layer of concrete is usually only 0.75 in. in thickness - the minimum cover specified by the ACI code. The concrete above the tension steel remains intact. Prior to the formation of secondary fragments, extensive transverse cracking occurs in the slab due to both bending and splitting action. The main bending cracks form a pattern which is not unlike the familiar static yield line development in R/C slabs. The splitting cracks, caused by wedging of the deformed reinforcing bars, occur over the rods on the tension face. A number of examples clearly illustrate the rectangular grid of cracks corresponding to the layout of the reinforcement. This feature limits the maximum size of a secondary fragment to that of a 0.75 in. plate with the dimensions of the reinforcing grid. A very small amount of chipping has been observed up to the 10 psi level; about 30 percent of

the concrete below the tension steel has been found to break loose at the 100 psi level. This latter case would represent about 560 lbs of small fragments from a 20 ft by 10 ft shear wall.

The central conclusion of this study, that R/C slabs do not contribute significantly to debris accumulation, is supported by three technical chapters dealing respectively with the loading, transport and response of R/C slabs. This result was entirely unanticipated at the outset of the present program which embraced the objective of describing the amount and character of debris generated by R/C slabs. Specifically, the program called for the review of the results of an experimental investigation conducted at the U.S. Army Engineer Waterways Experiment Station (WES) with a view toward using the findings to develop a fragmentation model. No fragmentation was achieved in this experimental study, and indeed, fragmentation was not within the purview of the investigation. For this reason, the approach of the present program had to be altered and efforts were finally directed toward a reexamination of the blast effects literature from the standpoint of fragmentation.

It is perhaps not surprising that only a small part of the blast effects literature is useful in the study of slab fragmentation. Nevertheless, it is felt that enough results are available to support the inferences that have been drawn. We have adopted the case method in our description of relevant papers and reports and have endeavored to reproduce the significant photographs upon which we have based our observation. We believe that the case method is the most objective way to justify our conclusions; however, we are aware that this method characteristically tells a story in a telegraphic style. In our final chapter, the case method is abandoned in favor of a rather subjective discussion of results.

CHAPTER II

LOADING

The loading on slabs depends upon both their initial orientation and their post cracking behavior. Several preliminary remarks are in order concerning the general employment of R/C slabs as it relates to their orientation. Certainly the predominant use of slabs in above grade structures is in roof and floor elements. We shall see that the horizontal disposition of these members precludes any significant transverse loading in the Mach region of a nuclear environment where the shock front is nearly vertical. Although R/C curtain walls are almost never used, vertical R/C slabs are found in special circumstances in the form of shear walls. We shall describe a rough guide to the use of shear resisting members.

In R/C buildings of the frame/slab or flat/slab types, no shear walls are needed for buildings under 10 to 12 stories. From about 10 to 20 stories, R/C core walls may be used around elevator shafts and stairwells. For buildings over 20 stories shear is resisted by combinations of:

a. Frames

b. Exterior shear walls

c. Interior shear walls (in place of some partitions)

In such buildings, shear walls are not required in the top 12 to 15 stories. Where earthquake design is employed, shear walls are required up to about 15 stories. Over this, shear is resisted either by the frame alone or a combination of frame and shear walls. Multistory steel buildings up to 25 stories usually have R/C core walls around their elevator shafts and stairwells. Over 25 stories, shear may be resisted by X-bracing or by interior shear walls.

Title: Model Analysis

Author: Davies, L. Ll.

Source: Proceedings of the Symposium on Protective Structures for Civilian Populations, National Academy of Sciences National Research Council

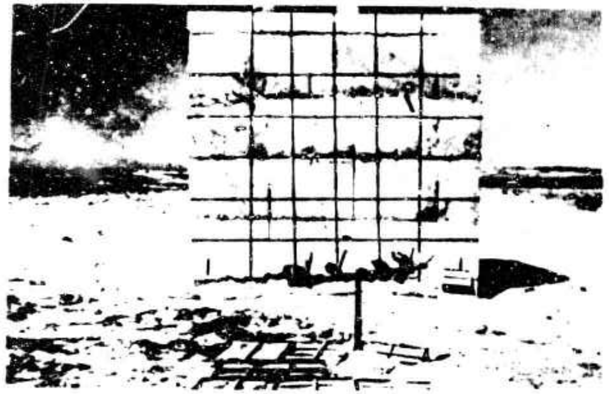
Date: April 19-23, 1965

Conclusion I: Complete primary fragmentation may be impossible in R/C slabs where the reinforcement is continuous from the slab into the supporting structure. In such cases, fracture of the steel in the center of the slab will merely permit the resulting petals to "weathervane," i.e. to unload themselves by aligning with the wind.

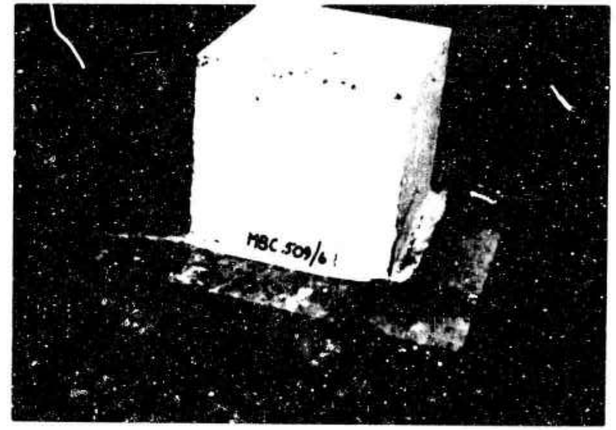
Remark I: Post-test photographs of R/C cubicles which were subjected to the blast loading are shown in Figure 1. In the case of both the scale model and the full size cubicle, failure was in the nature of the steel fracturing along the diagonals with the resulting petals bending back out of the wind.

Conclusion II: Reinforced concrete walls parallel to the direction of the blast wind and horizontal slabs above grade will not fail because, due to their orientation, they will not experience any transverse loading.

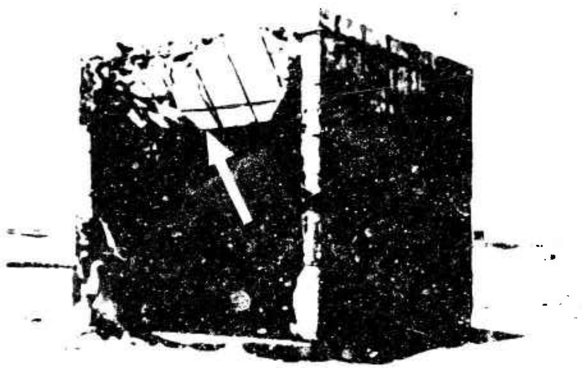
Remark II: None of the side walls or roof slabs in the R/C cubicles shown in Figure 1 exhibit any damage.



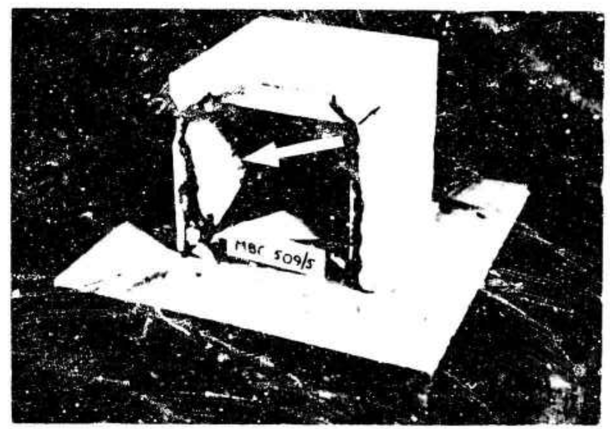
10 psi



15 psi



34 psi
Full-Scale



21 psi
1/24 Scale

Figure 1 REINFORCED CONCRETE CUBICLES AFTER DYNAMIC LOADING

Title: The Effects of Nuclear Weapons

Editor: Glasstone, Samuel

Source: U. S. Department of Defense, U. S. Atomic Energy Commission

Date: February 1964

Conclusion I: In buildings with exterior wall openings (windows, doors, etc.), only the ground level floor is subjected to a significant transverse loading due to a nuclear blast.

Remark I: Two-story wood-frame houses were exposed to the air blast from a nuclear weapon. A postshot photograph of the exterior of the house at the 2.6 psi overpressure range is shown in Figure 2. The damage to the first floor joists in this house is shown in Figure 3 and the even more severe damage to the first floor joists of a similar house at the 4 psi overpressure range is shown in Figure 4. However, even in the house at the 4 psi range, the second floor showed little damage - thus indicating rapid pressure equalization above and below the floor.

Conclusion II: Under favorable conditions, R/C structures may receive virtually no damage from a nuclear blast.

Remark II: Although the reinforced concrete deck bridge shown in Figure 5 was only 270 ft from ground zero at Hiroshima, it showed no sign of any structural damage. Thus, due to the fact that the loading was primarily vertical and the possibility that the magnitude may have been diminished by reflections of the blast wave off the water onto the underside of the bridge, the bridge apparently just deflected downward under the blast wave and rebounded, leaving only a slight net displacement.

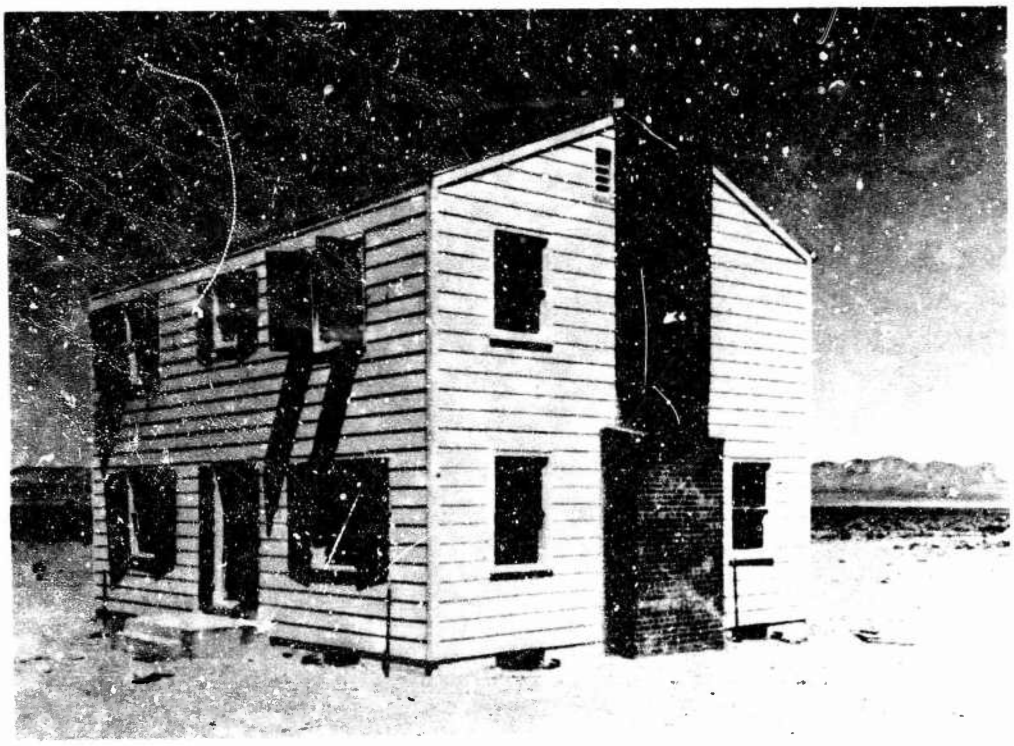


Figure 2 STRENGTHENED WOOD FRAME HOUSE AFTER EXPOSURE TO 2.6 PSI OVERPRESSURE

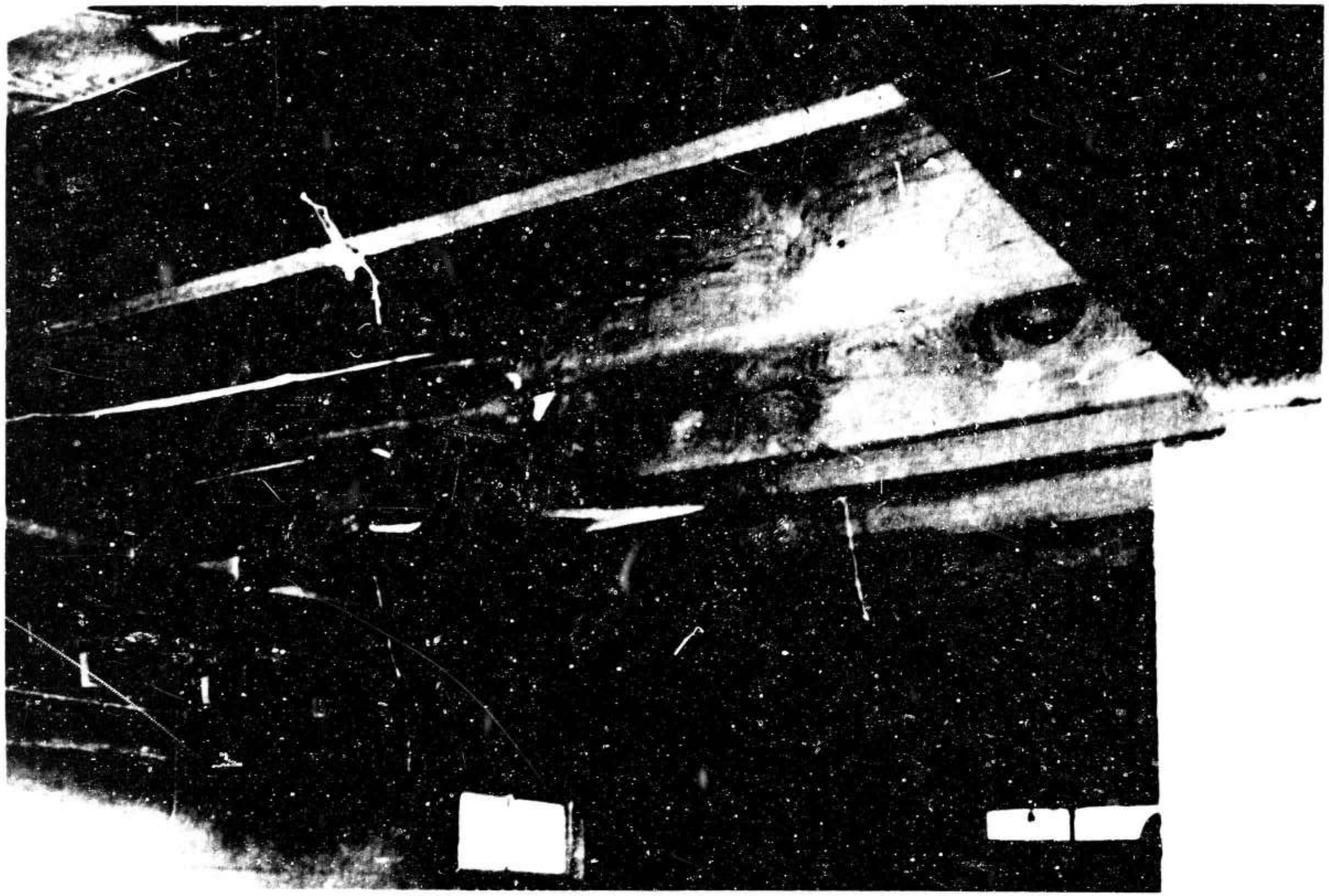


Figure 3 FIRST FLOOR JOISTS OF STRENGTHENED WOOD FRAME HOUSE EXPOSED TO 2.6 PSI OVERPRESSURE

Figure 4 FIRST FLOOR JOISTS OF STRENGTHENED WOOD FRAME HOUSE EXPOSED TO 4 PSI OVERPRESSURE

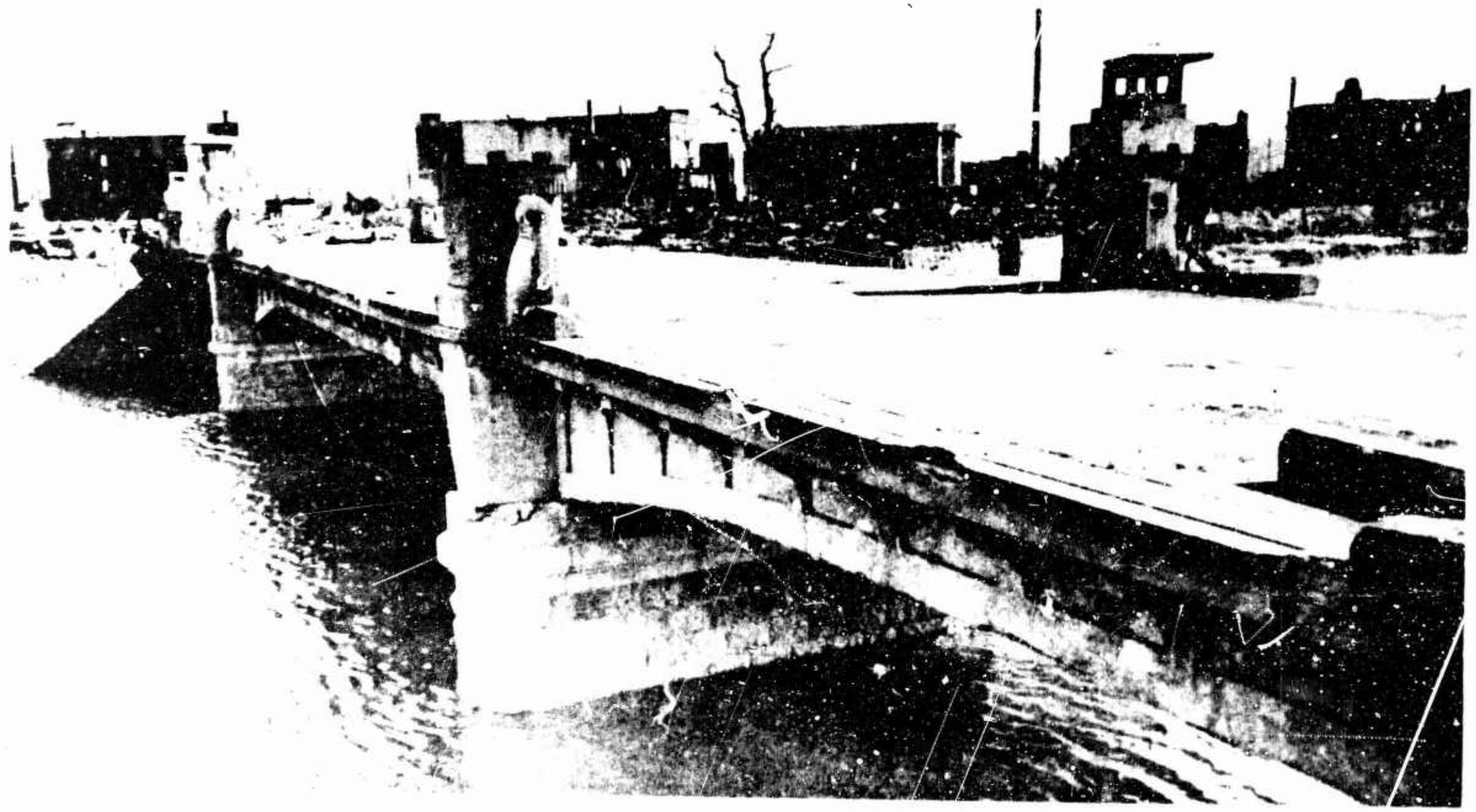


Figure 5 STEEL PLATE GIRDER BRIDGE WITH R/C DECK AND CONCRETE FACING ON OUTER GIRDER LOCATED 270 FT FROM GROUND ZERO AT HIROSHIMA

CHAPTER III

FRAGMENT TRANSPORT

In our next chapter we shall show that potential R/C slab fragments are either very large or small, i.e., the size of a full slab with a ballistic coefficient of about 1500 lb/ft^2 or the size of a brick with a ballistic coefficient of 50 lb/ft^2. On this basis we can make several observations that are relevant to the horizontal displacement of fragments. These observations are necessarily limited because high rise R/C buildings have never been exposed to nuclear blast loadings.

Title: The Effects of Nuclear Weapons

Editor: Glasstone, Samuel

Source: U. S. Department of Defense, U. S. Atomic Energy Commission

Date: February 1964

Conclusion I: High burst heights give rise to smaller fragment translation.

Remark I: For structures close to ground zero, high altitude bursts subject their roof and floor slabs to large downward pressure components. This pressure augments the gravitational acceleration and shortens the flight time of the fragments. Since the horizontal component of the dynamic pressure acts on the fragments for a shorter time, they undergo smaller translations.

The effects of high altitude detonations is clearly indicated in Figure 6 which shows a heavily dished R/C roof slab. This structure was located only 0.10 mile from ground zero at Hiroshima.

Conclusion II: Potential fragments from R/C shear walls or panels will tend to remain on the building site.

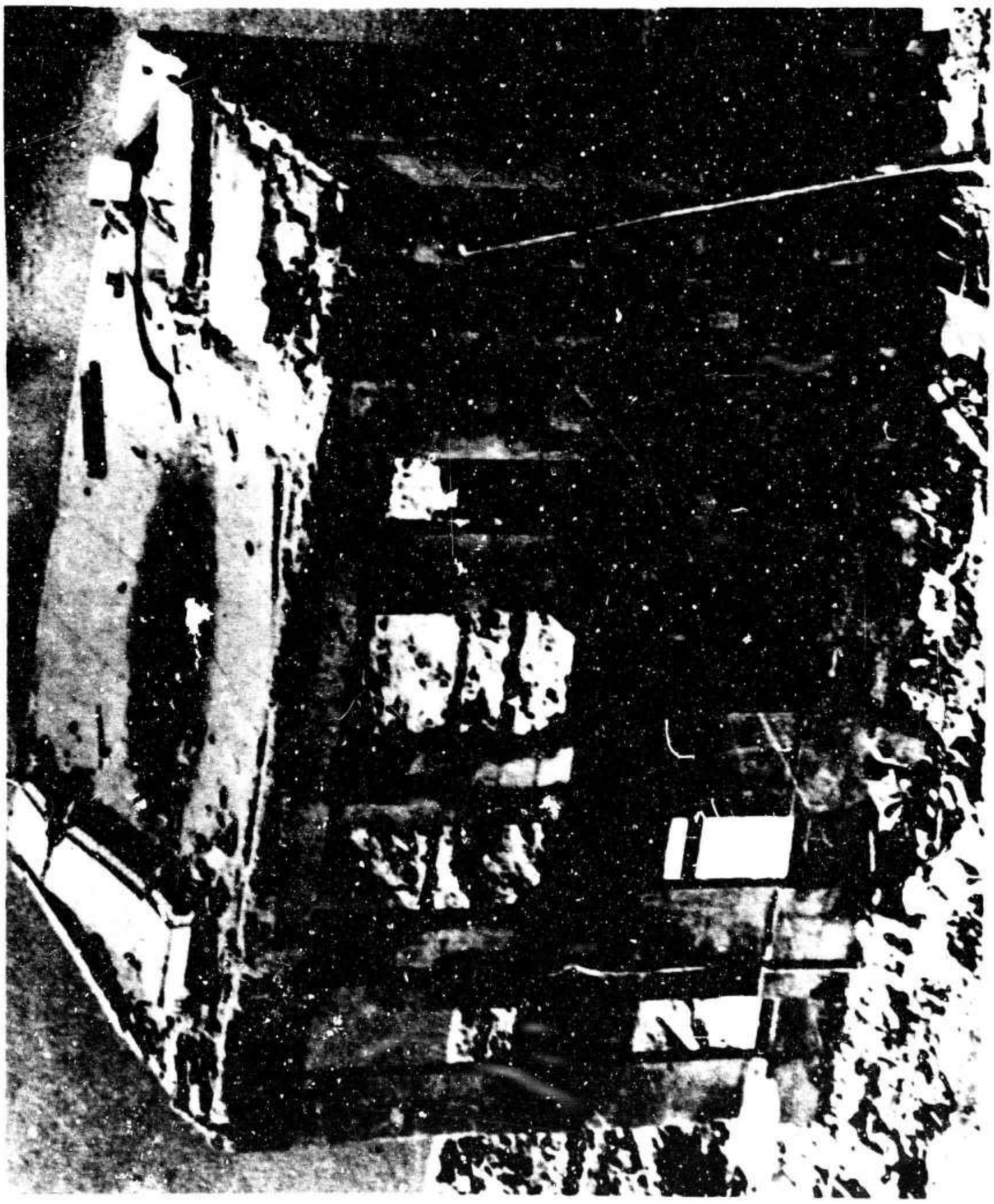


Figure 6 REINFORCED CONCRETE BUILDING LOCATED 0.10 MI FROM GROUND ZERO AT HIROSHIMA

Remark II: When shear walls are used in the core of a building they are often located at a distance of two bays or 40 ft from the curtain walls. Thus, any fragments generated from these members will have to travel about 50 ft before they threaten to congest the nearest street. There is considerable evidence to show that the small secondary fragments which we anticipate can easily surpass 50 ft in translation. This is demonstrated by the aerial survey of tornado damage shown in Figure 7. The tornado produces dynamic pressures which are not unlike those created by a large hydrogen bomb at the 5 psi level.

We anticipate that potential primary fragments will have dimensions of the same order of magnitude as the full size slab. To get some idea of the response of such large fragments we can examine the structures shown in Figures 8, 9 and 10. The first of these shows a massive section of wall that was dislodged from the structure at a height of 60 to 70 ft. We estimate that the fragment was transported 14 ft horizontally. The structure was located at a distance of 0.34 miles from ground zero. The photographs shown in Figures 9 and 10 show two engine lathes weighing 7000 and 12,000 lb respectively. The small lathe displaced about 7 ft under a 10 psi overpressure; the large lathe, with a ballistic coefficient about 7 times greater, did not move from its anchors. As a final example, primary fragments have been produced from the brick chimneys of the two houses shown in Figures 11 and 12. In both cases, the final position of the primary fragments was in the immediate vicinity of the base of the chimney.

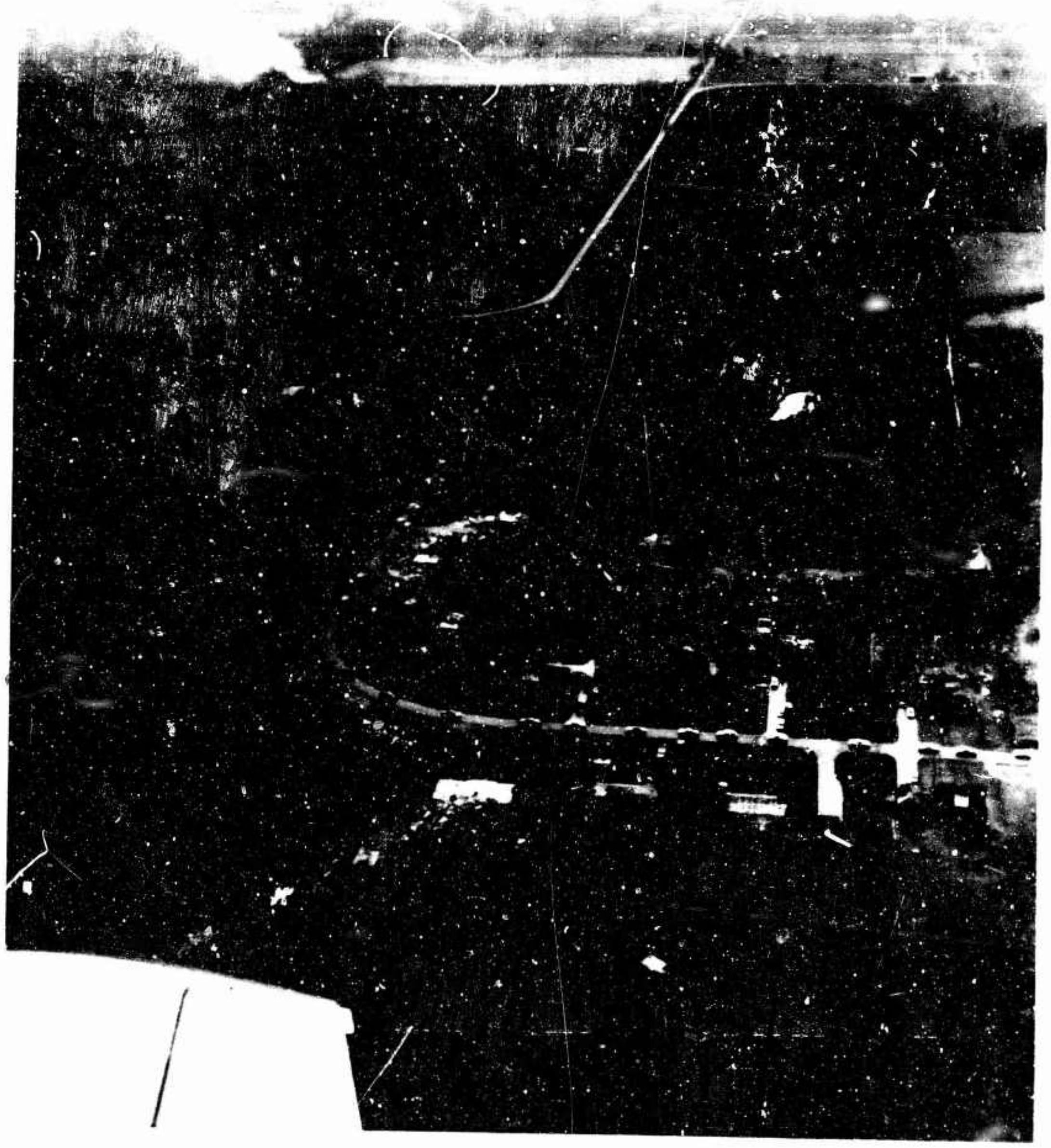


Figure 7 IIT RESEARCH INSTITUTE AERIAL PHOTOGRAPH OF PROPERTY DAMAGE IN ELKHART, INDIANA BY TORNADO ON APRIL 11, 1965

Figure 8 HEAVY WALL BEARING STRUCTURE LOCATED 0.34 MI FROM GROUND ZERO AT NAGASAKI

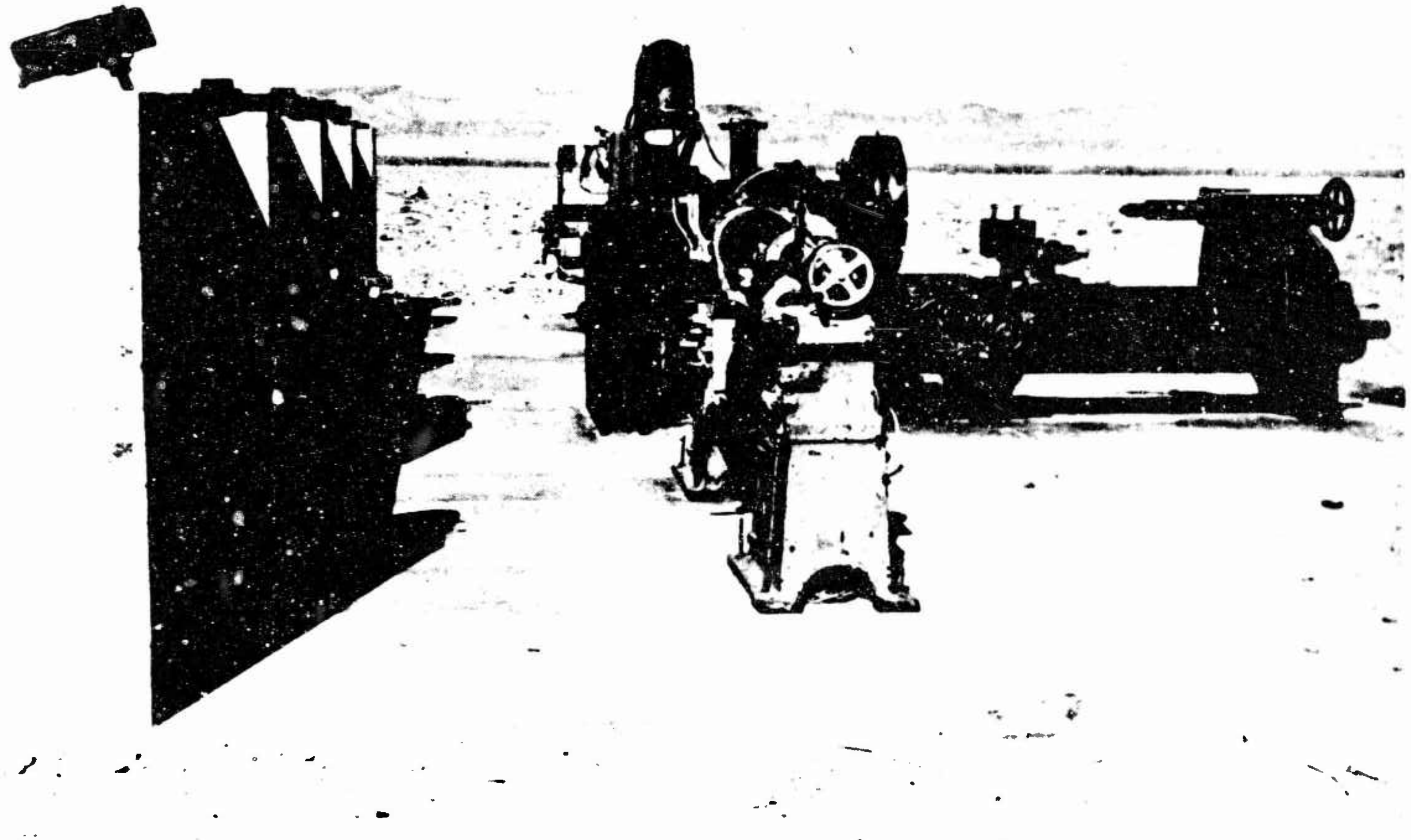


Figure 9 MACHINE TOOLS BEHIND MASONRY WALL IN NEVADA BEFORE 10 PSI OVERPRESSURE

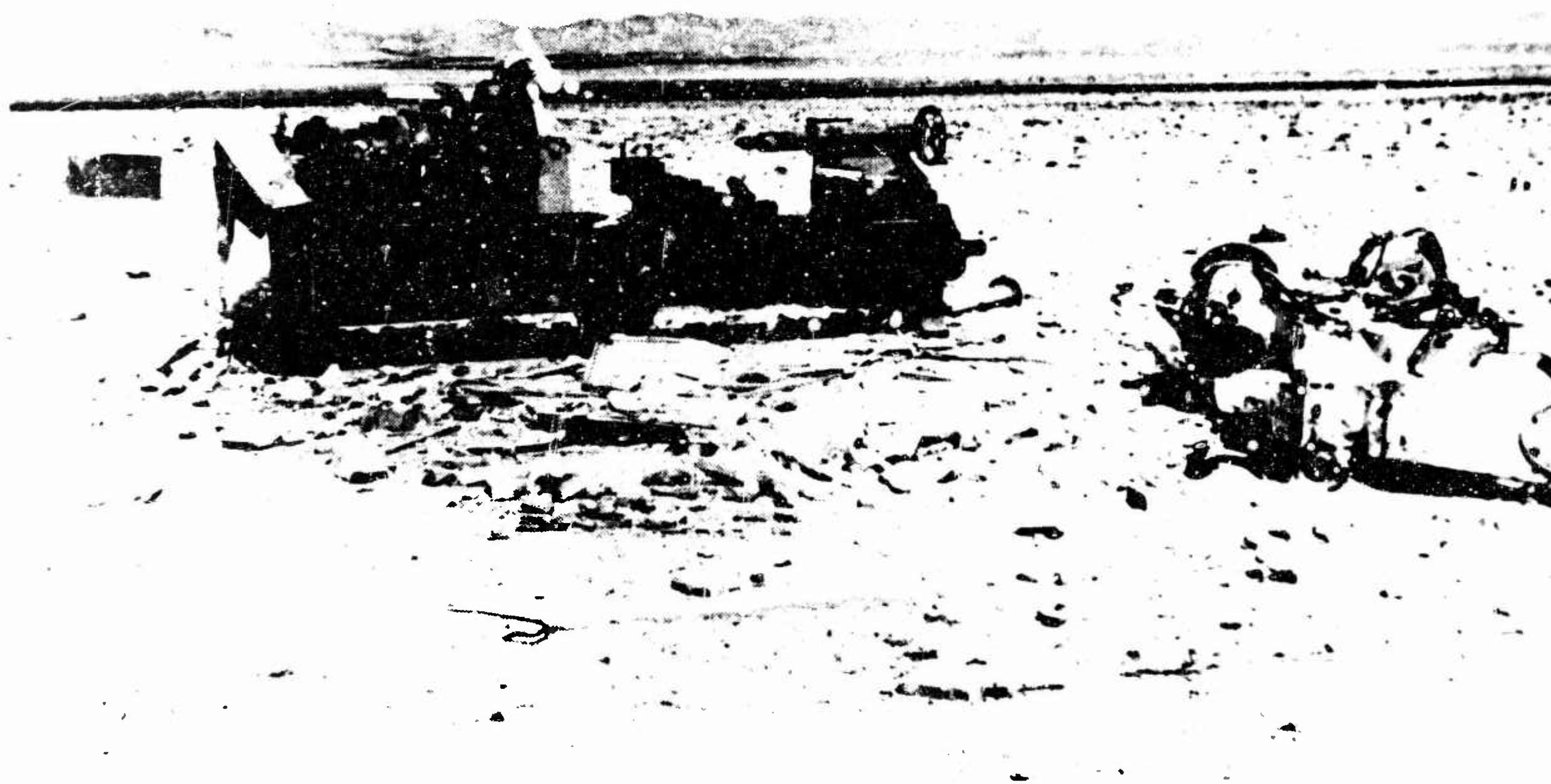


Figure 10 MACHINE TOOLS AFTER EXPOSURE TO 10 PSI OVERPRESSURE IN NEVADA

Figure 11 STRENGTHENED WOOD FRAME HOUSE AFTER EXPOSURE TO 4 PSI OVERPRESSURE

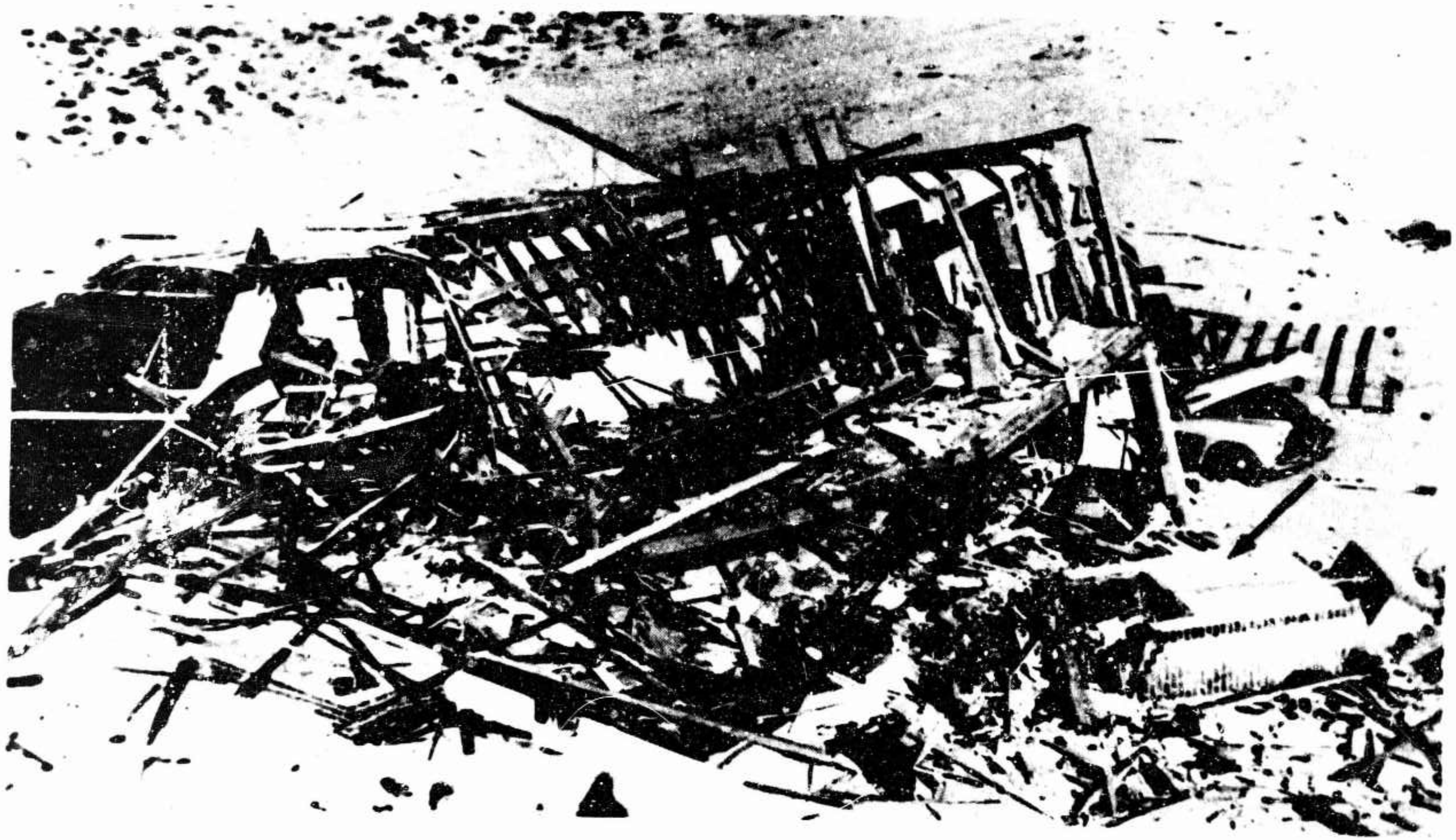


Figure 12 WOOD FRAME HOUSE AFTER EXPOSURE TO 5 PSI OVERPRESSURE

Title: Shelter Evaluation Program

Author: Heugel, W. F. and Feinstein, D. I.

Source: Office of Civil Defense, Contract OCD-PS-64-50
Work Unit 1614A

Date: February 1967

Conclusion: Large fragments tend to remain on the building site.

Remark: In Figure 42 of the subject reference, the effect of the ballistic coefficient on the debris trajectory is studied using analytical methods. Focusing our attention only on the range or maximum translation, we have plotted this parameter against the ballistic coefficient in Figure 13. The dashed line in this figure represents a conservative extrapolation to this curve of monotonically increasing curvature.

Based on the extrapolated curve, an entire 20 ft x 20 ft x 8 in. slab (Ballistic Coefficient = 1439) will translate less than 16.5 ft; a fragment one-fourth this size (Ballistic Coefficient = 903) will move less than 24 ft horizontally. A secondary fragment measuring 12 in. x 12 in. x 3/4 in. has a ballistic coefficient of about 88 and a range of 150 ft. As a conservative rule of thumb, these ranges increase as the square root of the height.

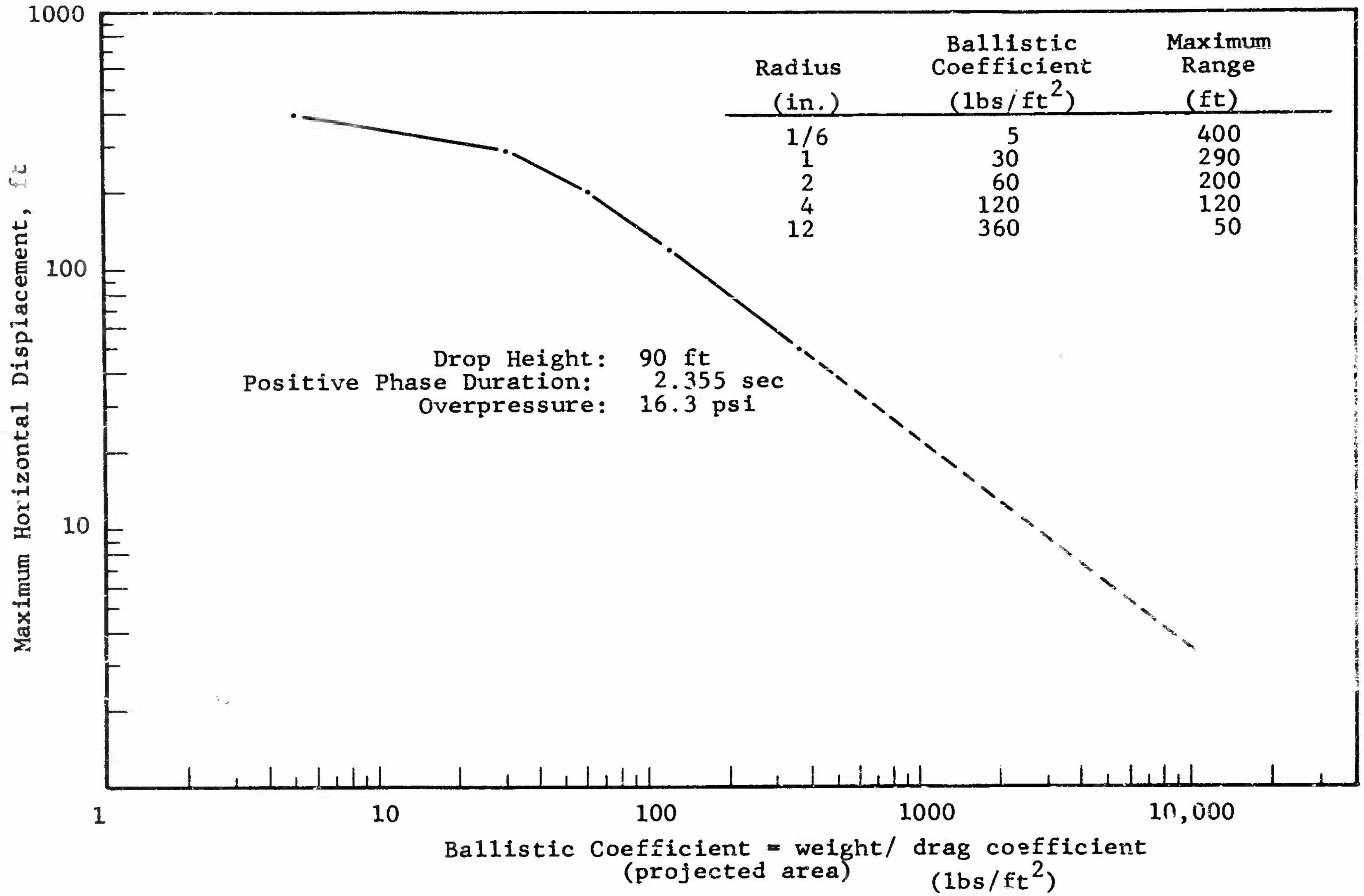


Figure 13 BALLISTIC COEFFICIENT VS RANGE FOR CONCRETE SPHERES

CHAPTER IV

RESPONSE

A. Introduction

Studies directed principally to the fragmentation of R/C slabs are almost nonexistent and, for this reason, we have chosen to examine the byproducts of investigations concerned with the analysis and design of conventional and blast resistant R/C structures. The most frustrating problem encountered in this approach is that the previous investigators were not motivated to report findings which are relevant to fragmentation. Also, most experimental work is confined to beams. Finally, these programs are generally concerned with only the range of behavior up to severe cracking. Unlike the homogeneous concrete bending members, this cracking is a necessary but not sufficient condition for the production of primary fragments. Indeed, tension cracks are always present in a R/C bending member under working loads; they become visible in great profusion under higher loads as shown in Figure 14.

Our studies of slab response have indicated that primary fragments are likely to occur in only two situations; punching out of the entire slab by shear at the boundaries or by large deflections of simply supported slabs which cause the entire slab to push through their supports. The strength and ductility of the steel reinforcement together with the difficulty of sustaining loads on cracked slabs operate to prevent the formation of small primary fragments. The problems of primary and secondary fragments in slabs will be dealt with separately in this chapter; but, first we shall explore the implications of high tenacity in other types of R/C members.

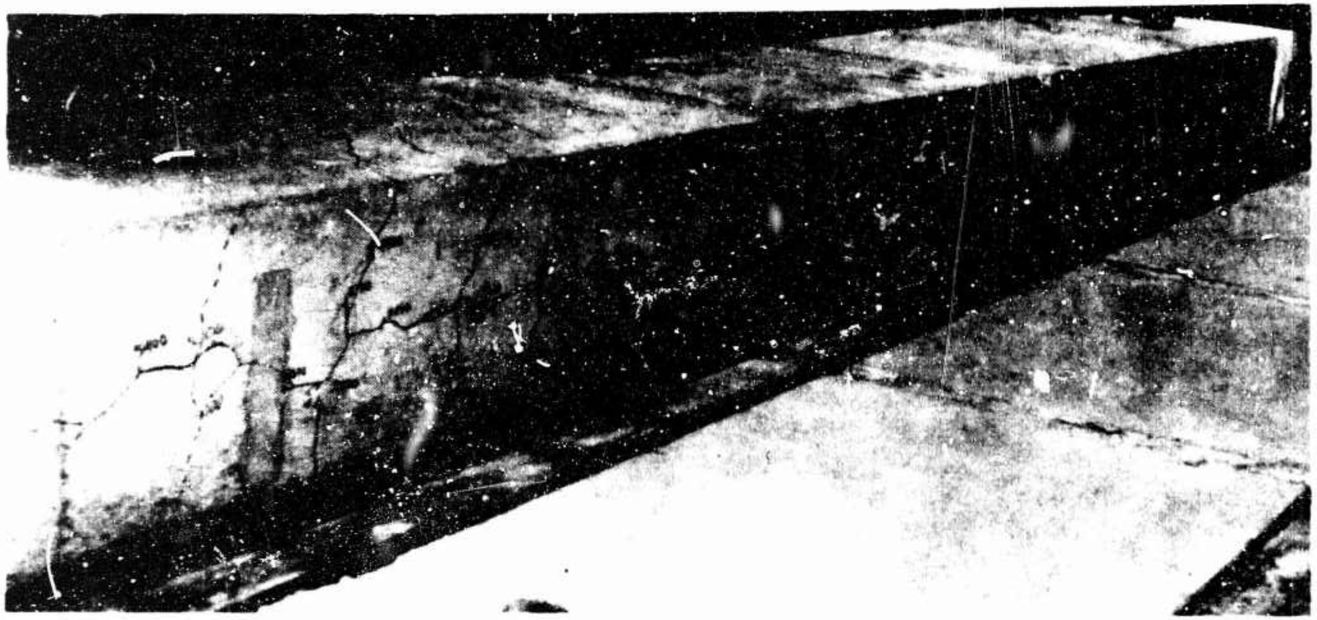


Figure 14 LONGITUDINAL CRACKING OVER CONSTANT MOMENT LENGTH (MIDDLE THIRD) WITH SINGLE REINFORCING BAR

Title: The Effects of Nuclear Weapons

Editor: Glasstone, Samuel

Source: U. S. Department of Defense, U. S. Atomic Energy Commission

Date: February 1964

Conclusion I: Primary fragmentation does not necessarily accompany general and complete destruction of R/C frame and panel buildings.

Remark I: The R/C building shown in Figure 15 was located 0.26 mile from ground zero at Nagasaki. Hinge points can be identified in the beams over the window openings and hinge lines in the panels. The destruction is quite complete and yet we note that because none of the reinforcement has ruptured the building remains in one piece. There is therefore no primary fragmentation.

Conclusion II: Primary fragmentation does not necessarily attend the complete and general destruction of R/C frame buildings.

Remark II: A three story R/C frame building which is typical of conventional American construction is shown in Figure 16. Located only 0.13 mile from ground zero at Hiroshima, the building suffered enormous damage. The ends of many beam and column members have been completely severed through their reinforcement. We observe, however, that there is at most one free end on each member; the other is still attached to the structure. There is no primary fragmentation of the frame since the entire structure is tied together by the steel. Much of the observed fragmentation is composed of pieces of brick panel which made up the 13-in. thick walls.

Figure 15 ONE STORY R/C BUILDING WITH SHEET ROOF TRUSSES LOCATED 0.26 MI FROM GROUND ZERO AT NAGASAKI

Figure 16 THREE STORY R/C FRAME BUILDING WITH BRICK WALL PANELS LOCATED 0.13 MI FROM GROUND ZERO AT HIROSHIMA

Conclusion III: When large R/C stacks are severely damaged by a nuclear explosion, primary fragmentation may still be incomplete with the major fragments remaining linked together by the steel reinforcement.

Remark III: A circular 60-ft high R/C stack located 0.34 mile from ground zero at Hiroshima was very severely damaged by the blast wave. Referring to Figure 17, it is observed that the stack remained intact up to a height of 15 ft above the base. The top 45 ft has been toppled over and now consists of two relatively intact sections and the top section which has been completely pulverized. The reinforcing rods continue to link all the major fragments together. The top section of the stack where the steel is completely exposed probably was denuded when that section impacted the ground.

Figure 17 CIRCULAR 60-FT HIGH R/C STACK LOCATED 0.34 MI FROM GROUND ZERO AT HIROSHIMA

Title: Blast Effects of Atomic Weapons Upon Curtain Walls and Partitions of Masonry and Other Materials

Author: Taylor, Benjamin C.

Source: Operation Upshot-Knothole, WT-741, DDC No. AD-636 766

Date: August 1956

Conclusion: Reinforced masonry is considerably more blast resistant than unreinforced masonry.

Remark: A front wall consisting of 4 in. of brick facing and 4 in. of clay tile backing was located at the 4.5 psi overpressure range. Figure 18 shows a motion picture sequence of the failure of this wall. In the fourth frame it appears that a primary fracture pattern has formed which consists of a central rectangular crack pattern with cracks running diagonally from the corners of the central rectangle out to the corners of the panel. Postshot examination revealed that the wall was 98 percent blown into the cell with the bottom corners remaining. An 8 in. reinforced grouted brick masonry rear wall was tested at the 7.5 psi overpressure range. The resulting damage consisted of some crushing at the top on the outside face and a 3 ft long crack on the inside face which ran from the top down to near the center of the wall. Even this small amount of damage may have been prevented, if the wall panel had been properly tied into the roof slab with continuous bars. Front and rear walls consisting of 8 in. of R/C with keyed joints at the top and bottom were also tested at the 7.5 psi overpressure range. Preshot and postshot photographs of these walls are shown in Figure 19. Only the front wall received any observable damage. It had a 4 ft long horizontal crack on the outside face near one edge at the ground and a hairline opening of the construction joint.

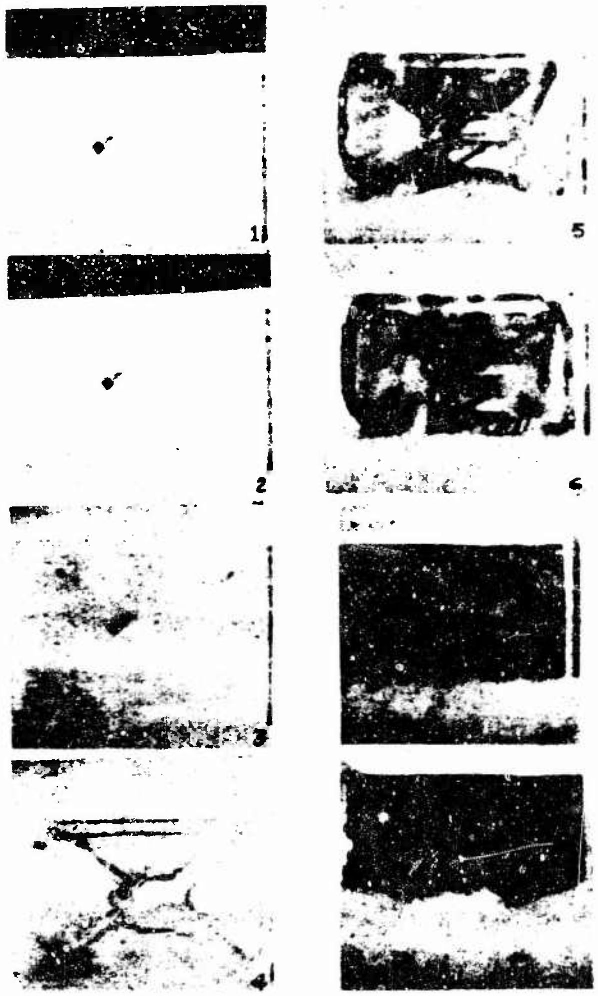


Figure 18 MOTION PICTURE SEQUENCE OF FAILURE OF UNREINFORCED MASONRY WALL UNDER 4.5 PSI OVERPRESSURE

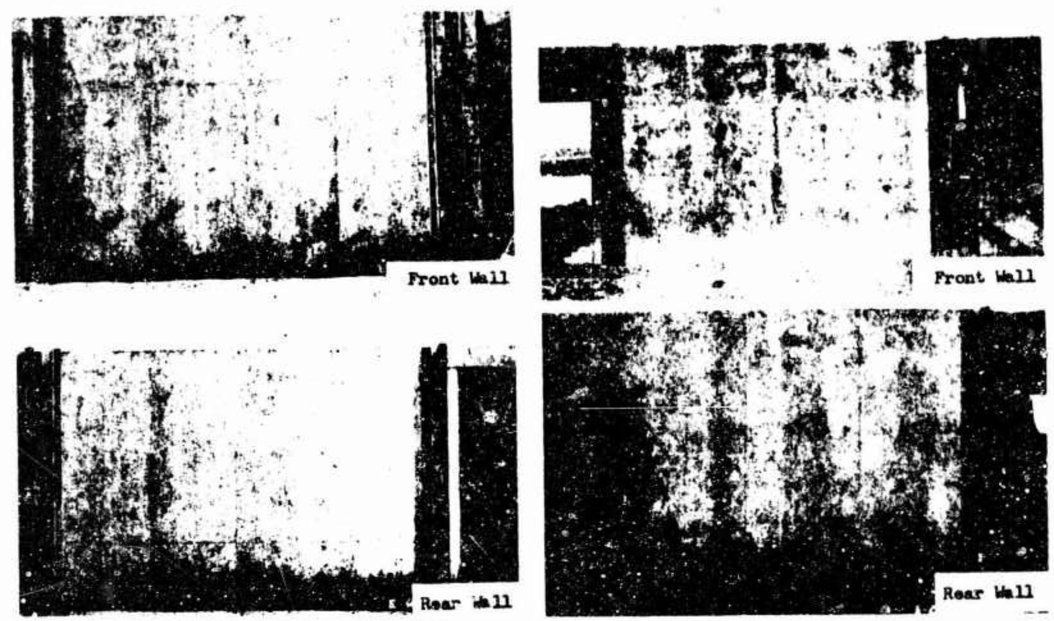


Figure 19 PRESHOT AND POSTSHOT PHOTOGRAPHS OF R/C WALL AT 7.5 PSI OVERPRESSURE RANGE

Title: Fibrous Reinforcements for Portland Cement Concrete

Author: Williamson, G. R.

Source: U. S. Army Engineer Division, Ohio River Corps of Engineers Technical Report 2-40

Date: May 1965

Conclusion: The tenacity of a concrete slab under a point high explosive charge is greatly increased by the addition of a small amount of reinforcing.

Remark: High explosive tests were conducted in 36 x 36 x 4 in. concrete slabs. The dynamic pressure loading created by the 2.5 lb charge was in excess of 4000 psi. As illustrated in Figure 20, the plain concrete slab was completely destroyed while the R/C slab was only breached. The reinforcement in the second slab consisted of one percent of steel wire, 1 in. in length and 0.01 in. in diameter, randomly oriented and 2 in. by 2 in. wire mesh in the center of the slab.

Title: Investigation of the Structural Properties of Reinforced Concrete Masonry

Author: Saemann, Jesse C.

Source: National Concrete Masonry Association

Date: June 1955

Conclusion: The reinforcing steel does not fracture in R/C beams under static or impact loads.

Remark: The response of the R/C block beam shown in Figure 21, is typical of most monolithic R/C beam behavior under either static or impact loading. Yielding of the bars is not uncommon and it is usually followed by horizontal cracking which tends to expose portions of the tension steel by stripping away the concrete from the tension face of the beam. Literally no beam tests were encountered where fracture took place in the reinforcement. The literature survey included all of the issues of the Journal of the American Concrete Institute from 1955 through 1967.

a) Plain Concrete Slab After Testing with High Explosive

b) Wire-Reinforced Concrete Slab After Testing with High Explosive, 1 percent, 0.010 in., 1 in. Lengths

Figure 20 EFFECT OF WIRE REINFORCEMENT ON TENACITY OF CONCRETE SLABS EXPOSED TO HIGH EXPLOSIVE LOADINGS

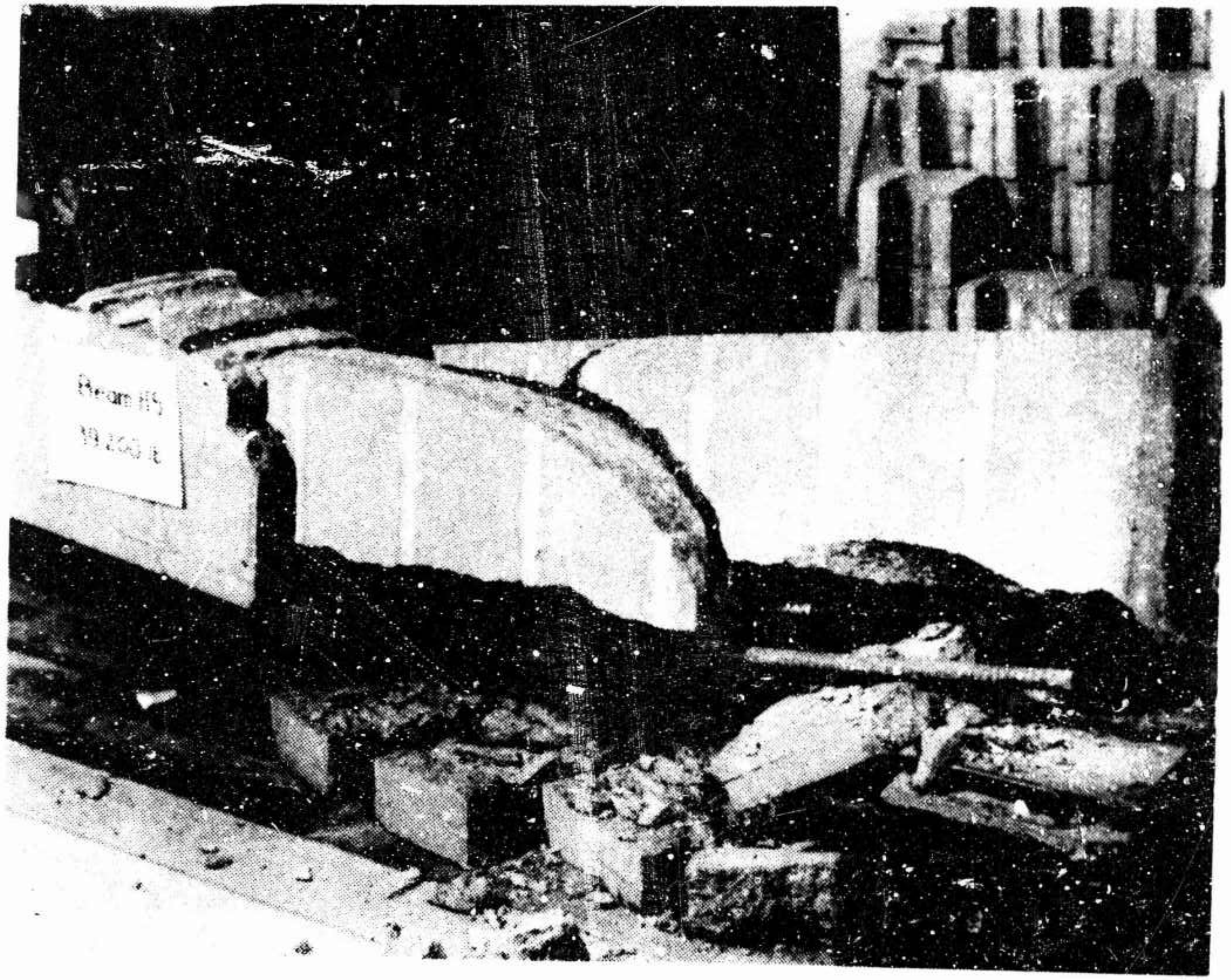


Figure 21 PRIMARY YIELD FAILURE OF A R/C BLOCK BEAM WITH SECONDARY SHEAR FAILURE THROUGH CONCRETE FILL AND MASONRY

Title: A Dynamic Ultimate Strength Study of Simply Supported Two-Way Reinforced Concrete Slabs

Author: Denton, D. R.

Source: U. S. Army Engineer Waterways Experiment Station Final Report, Contract OCD-PS-65-44, Office of Civil Defense

Date: April 1967

Conclusion: It is possible to fracture some of the tension steel in a R/C slab if it is lightly reinforced.

Remark: The steel reinforcement failures shown in Figure 22 were the only ones observed in a series of four static and 17 dynamic tests on simply supported R/C slabs. The slab in which these failures occurred had been exposed to the highest dynamic overpressure in the series of slabs with the lowest percentage of steel. Also, it is of interest to note that the failures occurred in the transition region where every other bar was bent up.

Title: Model Analysis

Author: Davies, I. Ll.

Source: Proceedings of the Symposium on Protective Structures for Civilian Populations, National Academy of Sciences National Research Council

Date: April 19-23, 1965

Conclusion: Steel reinforcement failures, which are necessary for primary fragmentation to occur, tend to occur along the static yield line patterns.

Remark: Steel failures occurred along the classic "x" static yield line pattern in the front wall of two of the R/C cubicles shown in Figure 1.

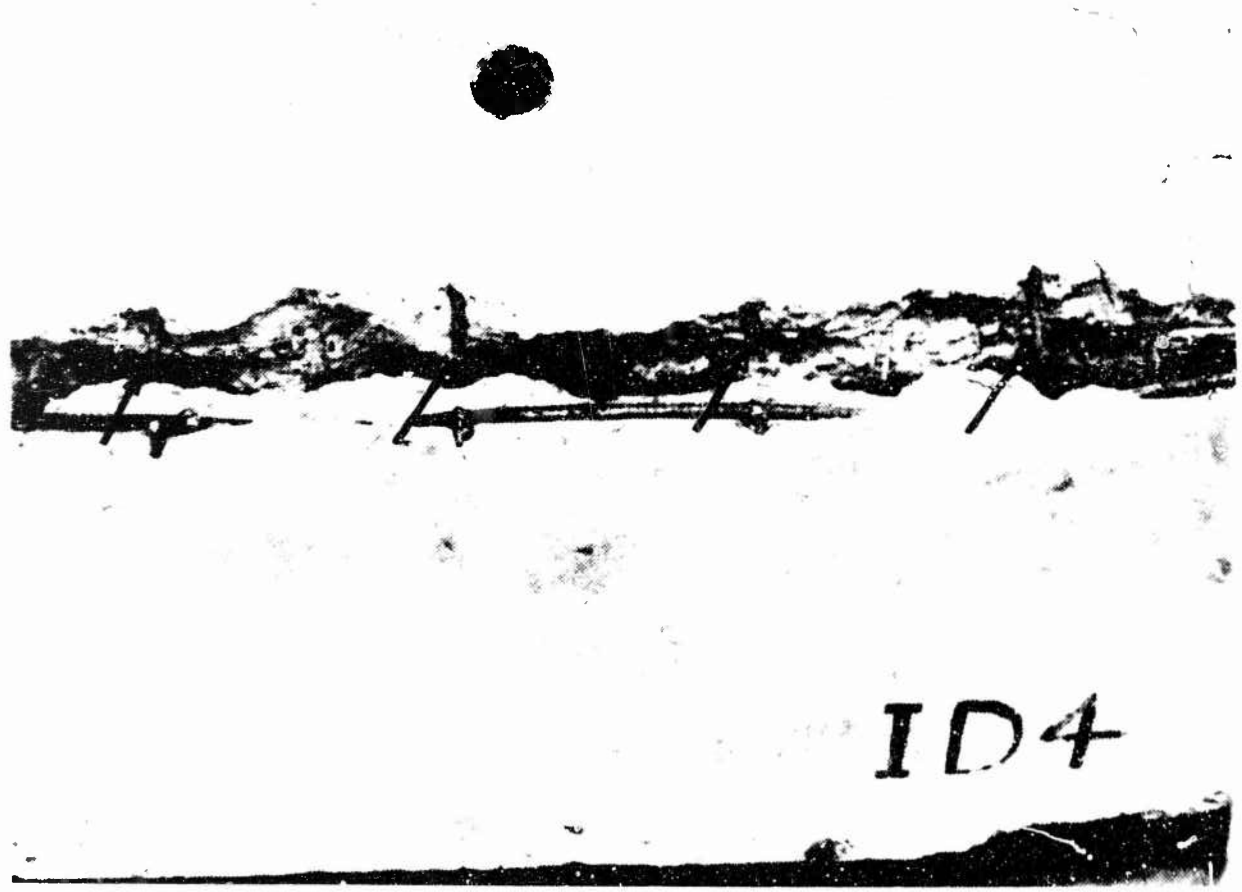


Figure 22 TENSION STEEL FAILURES NEAR THE EDGE OF A R/C SLAB WITH 0.78 PERCENT STEEL SUBJECTED TO 11.0 PSI OVERPRESSURE

Title: Resistance and Behavior of Concrete Slabs Under Static and Dynamic Uniform Loading with Edges Clamped and Laterally Restrained

Author: Keenan, W. A.

Source: Technical Report, Naval Civil Engineering Laboratory Port Hueneme, California

Date: To be published in 1968

Conclusion: No primary fragments are formed in R/C slabs subjected to dynamic pressures up to 120 psi.

Remark: The slab shown in Figure 23 has fixed edges which are laterally restrained. The member is typical of a series of R/C slabs which have been tested under uniform dynamic pressures as high as 120 psi. Although none of the reinforcing bars were fractured in the slab shown, necking down and fracturing occurred with some regularity near the edges of the slabs. In the most extreme case, such fracturing occurred in all the bars along two adjacent edges; however, primary fragments did not form because the slab segments were held together by the bars which remained attached to the intact edges.

When slabs exhibited large deflections (two to three times the slab thickness), their resistance was almost entirely due to tensile membrane action. In a few cases this tension caused some of the reinforcing bars to fracture in midspan. No primary fragments were obtained in the test series.

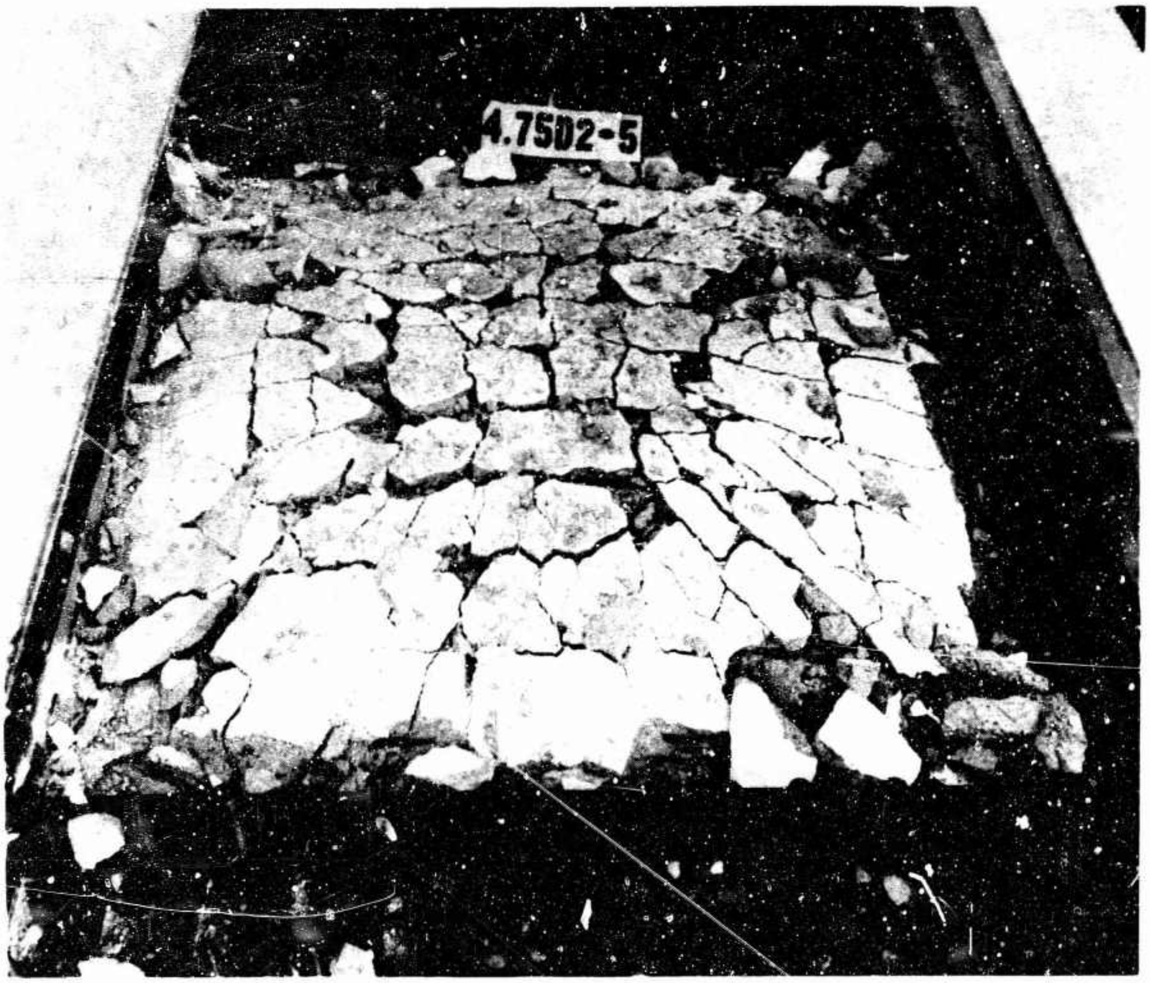


Figure 23 SLAB WITH EDGES FIXED AND LATERALLY RESTRAINED/ DYNAMIC PRESSURE LOAD OF 101 PSI

Title: Behavior of One-Way Concrete Floor Slabs Reinforced with Welded Wire Fabric

Authors: Atlas, A., Siess, C. P. and Kesler, C. E.

Source: J. Am. Conc. Inst., Proc., Vol.62(5) PP 539-557

Date: May 1965

Conclusion: Slabs reinforced with welded wire fabric fail suddenly by fracture of the reinforcing wire.

Remark: The longitudinal reinforcing wires in the one-way slabs investigated in the subject reference were anchored by rigidly welded transverse wires. In every case studied, the slabs failed by the sudden fracture of the steel while the concrete was apparently still intact on the compression face. It is highly significant that these are the only examples that could be found in the present program where the reinforcing steel was actually fractured under static loading. As far as we could determine, wire fabric is not generally used in shear walls.

Title: On the Dynamic Strength of Rigid-Plastic Beams under Blast Loads

Author: Salvadori, Mario G. and Weidlinger, Paul

Source: J. Eng. Mech. Div., ASCE Proc., pp 1389-1 to 1389-34

Date: October 1957

Conclusion: Under certain circumstances a slab under a uniformly distributed blast pressure may fail by developing plastic slides along the supports.

Remark: Shear failure of a reinforced concrete beam is accompanied by large changes in the bar geometries as shown in Figure 24 (Ref. 5). Ultimately, the shear resistance of the beam is provided by the tensile strength of the distorted reinforcing bars and, consequently, a plastic slide mechanism precedes rupture. The circumstances under which this failure mode occurs in beams is treated in the subject reference. In our opinion, the extension of these ideas to slabs is immediate.

If the slab is proportioned so that its bending strength is greater than its shear strength, it is possible, under sufficiently large pressures, to punch out the entire slab along its supports. The subject reference indicates that once plastic slides develop and the end slides cannot spread during bending and shear motion of the member.

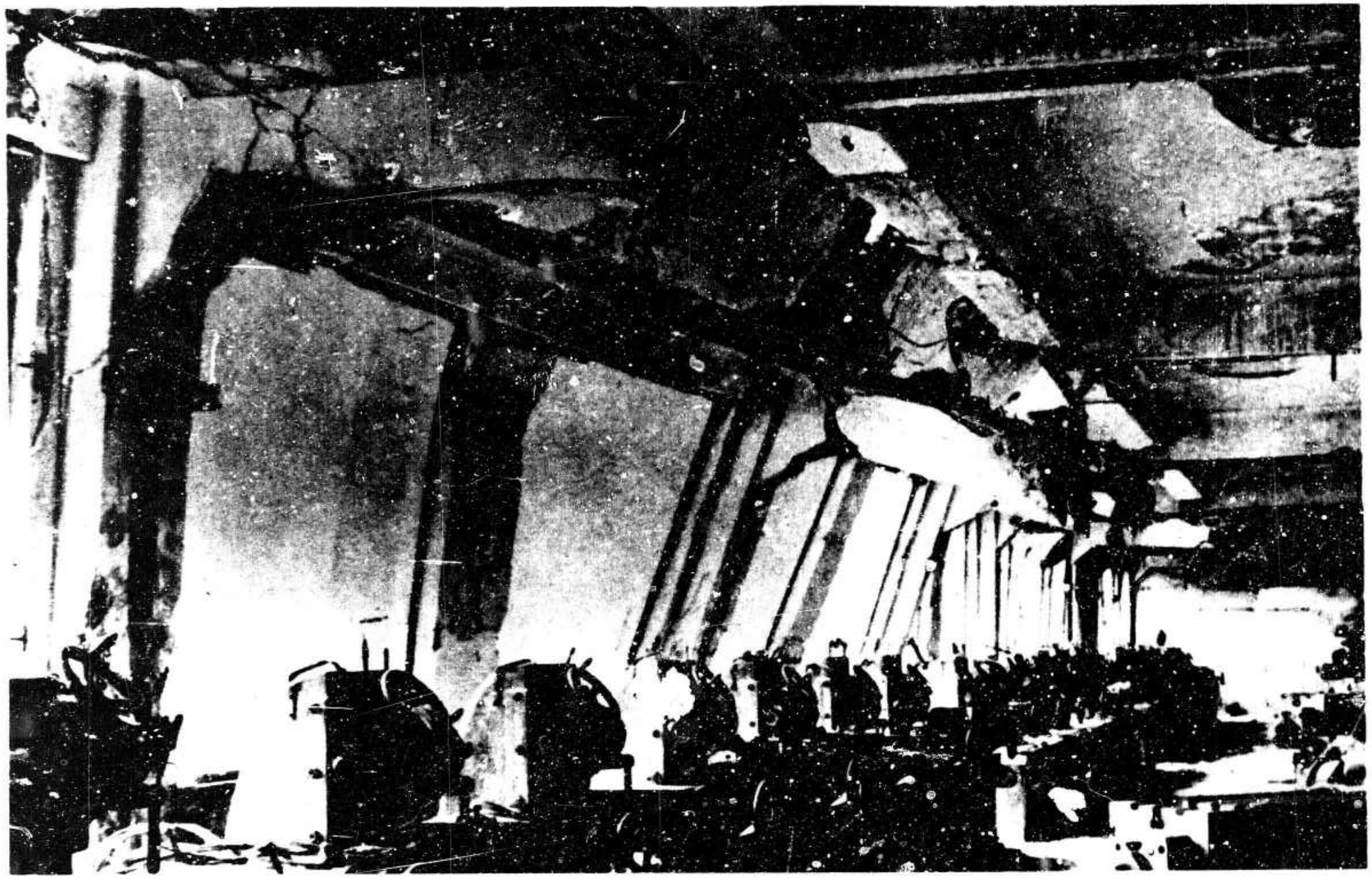


Figure 24 MULTISTORY R/C FRAME BUILDING SHOWING DOWELING EFFECTS IN THE BEAM REINFORCEMENT

B. Primary Fragments

The formation of a primary slab fragment requires fracturing of the reinforcing steel around the fragment periphery. The central question then is "what is the fracture mechanism of the steel?" It is surprising that in the hundreds of static and dynamic tests of R/C beams and slabs that were examined for this program, steel fracture was rarely encountered. Furthermore, no cases were found where these fractures were sufficient to produce a primary fragment.

To reconcile the fact that steel fracture is feasible but very unlikely, we can examine the possibility of obtaining the ultimate tensile strain in a deformed reinforcing bar. As loads are brought onto a bending member, the tensile strain in both the tension reinforcement and the concrete increase until the ultimate strain is achieved in the concrete. A flexure crack results and at this crack most of the tension is carried by the bars; the steel stress is maximum at such cracks. If we continue to increase the loading, the bar stress at the crack will also increase until either it yields or further loading is precluded by yielding at other locations in the bending member. Assuming that the bar yields at the crack, it would continue to stretch if the external loads were maintained or increased. If the elongation of the bar leads to the ultimate steel strain, fracture results; but, here we are led to the crux of the matter. How much of the bar participates in the elongation or over what gage length do we distribute the stretch?

Now, if only the portion of the bars included within a finite width crack participates in the elongation, very high strains will be quickly achieved and steel fracture will ensue. This is not, however, what happens. Even where shear is zero and moment constant, large local bond stresses exist adjacent to each flexural crack. These stresses cause a relative slip

between the steel and concrete which represents local loss of adhesion. This takes place in the pullout test by the time the bar carries only 2000 to 3000 psi.(Ref. 4). The slip near the crack gradually brings the lugs on the deformed bar into bearing against the surrounding concrete. These lugs tend to pry the concrete apart creating circumferential tension which in turn causes splitting of the concrete. This splitting enables a greater length of the bar to accommodate the stretch and, therefore, lower unit strains are realized.

When deformed bars are tested using a pullout specimen, failure nearly always occurs by splitting the concrete prism into two or three segments rather than by crushing against the lugs or by shearing on the cylindrical surface which the lugs tend to strip out. The splitting action can be seen as horizontal cracks in the constant moment section of the beam shown in Figure 14. Quoting from Ferguson (Ref. 4):

> "Splitting seems to start at flexure cracks being most evident where steel stress is largest. Thus splitting is a progressive phenomenon, working its way gradually along the length of embedment. Splitting may not be continuous from flexure crack to flexure crack. A splitting crack often stops short of the next flexure crack in a bond test beam; in fact the opening of a new flexural crack usually occurs beyond the end of a splitting crack, and added splitting then develops from the new flexure crack. Normally the splitting will eventually close the gap. Splitting can develop over 60 to 75 percent of the bar length without loss of average bond strength. Apparently splitting is one means by which some of the unevenness in bond stress distribution may be smoothed out. However, the final failure is sudden (in the absence of stirrups) as the split suddenly runs through to the end of the bar."

The implication of the splitting action is to free large portions of the bar to equalize the bending strain at values lower than the ultimate strain. There is, of course, a small chance that the splitting action will not rescue a strain concentration and then fracture can take place.

In slab elements which employ a wire fabric reinforcement, the splitting action can at best enable the strain to equalize between two nodes of the meshing since the orthogonal wires will anchor the nodes. One would expect more fractures of the reinforcement in welded wire fabric; but, only one reference is cited in support of this conjecture. It is quite common to use both tension and compression steel in a slab and, here, there is no possibility of breaching a member by bending alone. With the small concrete cover normally employed in slabs (3/4 in.) no suitable moment arm is available to put a tensile load in the compression reinforcement after severe cracking and fracture of the tensile steel. Fracture of the compressive steel must be brought about by membrane response. As a matter of fact, in the few cases where bars have ruptured the evidence suggests that fracture was brought about by a combination of bending and membrane action.

Title: A Dynamic Ultimate Strength Study of Simply Supported Two-Way Reinforced Concrete Slabs

Author: Denton, D. R.

Source: U. S. Army Engineer Waterways Experiment Station Final Report, Contract OCD-PS-65-44, Office of Civil Defense

Date: April 1967

Conclusion: The primary crack pattern produced in R/C slabs appears to be the same type of patterns predicted by yield line theory for ductile slabs.

Remarks: Figures 25, 26, 27 and 28 illustrate the crack patterns produced by uniformly distributed static and dynamic loads in simply supported R/C slabs. The slabs had a clear span of 7 ft-6 in. and were 2-5/8 in. thick. In each case, the primary crack pattern appears to consist basically of an inner square with diagonal cracks connecting the corners of the inner square to the corners of the slab.

Title: The Effects of Nuclear Weapons

Editor: Glasstone, Samuel

Source: U. S. Department of Defense, U. S. Atomic Energy Commission

Date: February 1964

Conclusion: Reinforced concrete wall panels may develop primary crack patterns similar to the classic static yield line patterns for ductile panels.

Remark: The wall panels on the R/C frame building 0.68 mile from ground zero at Nagasaki, shown in Figure 29, have primary cracks tending to occur along the diagonals. These panels may be considered to have fixed edges and thus the static yield line pattern would consist of yield lines occurring along the diagonals and the edges.

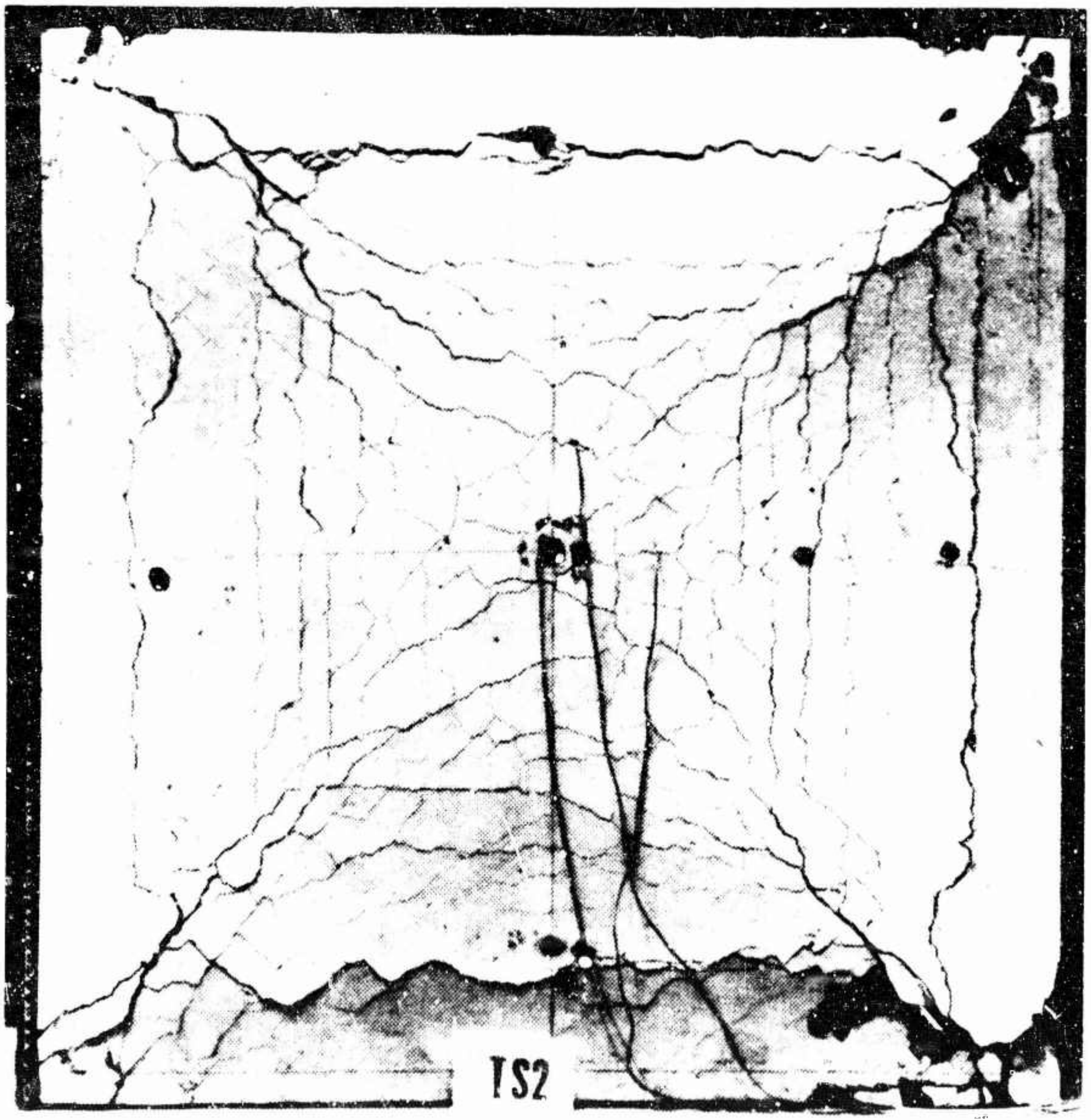


Figure 25 TENSION SURFACE OF R/C SLAB WITH 0.78 PERCENT STEEL SUBJECTED TO 7.1 PSI UNIFORM STATIC LOADING

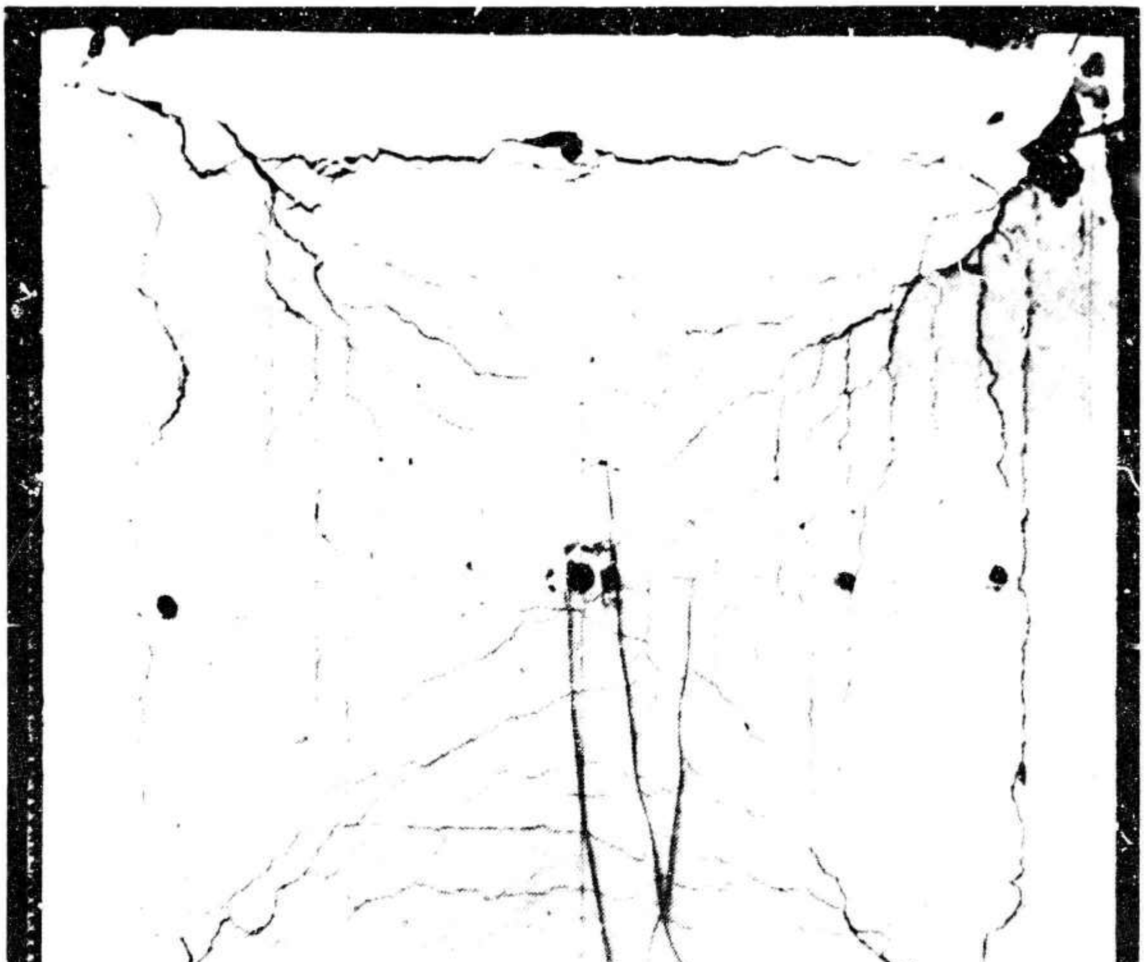


Figure 25 TENSION SURFACE OF R/C SLAB WITH 0.78 PERCENT STEEL SUBJECTED TO 7.1 PSI UNIFORM STATIC LOADING

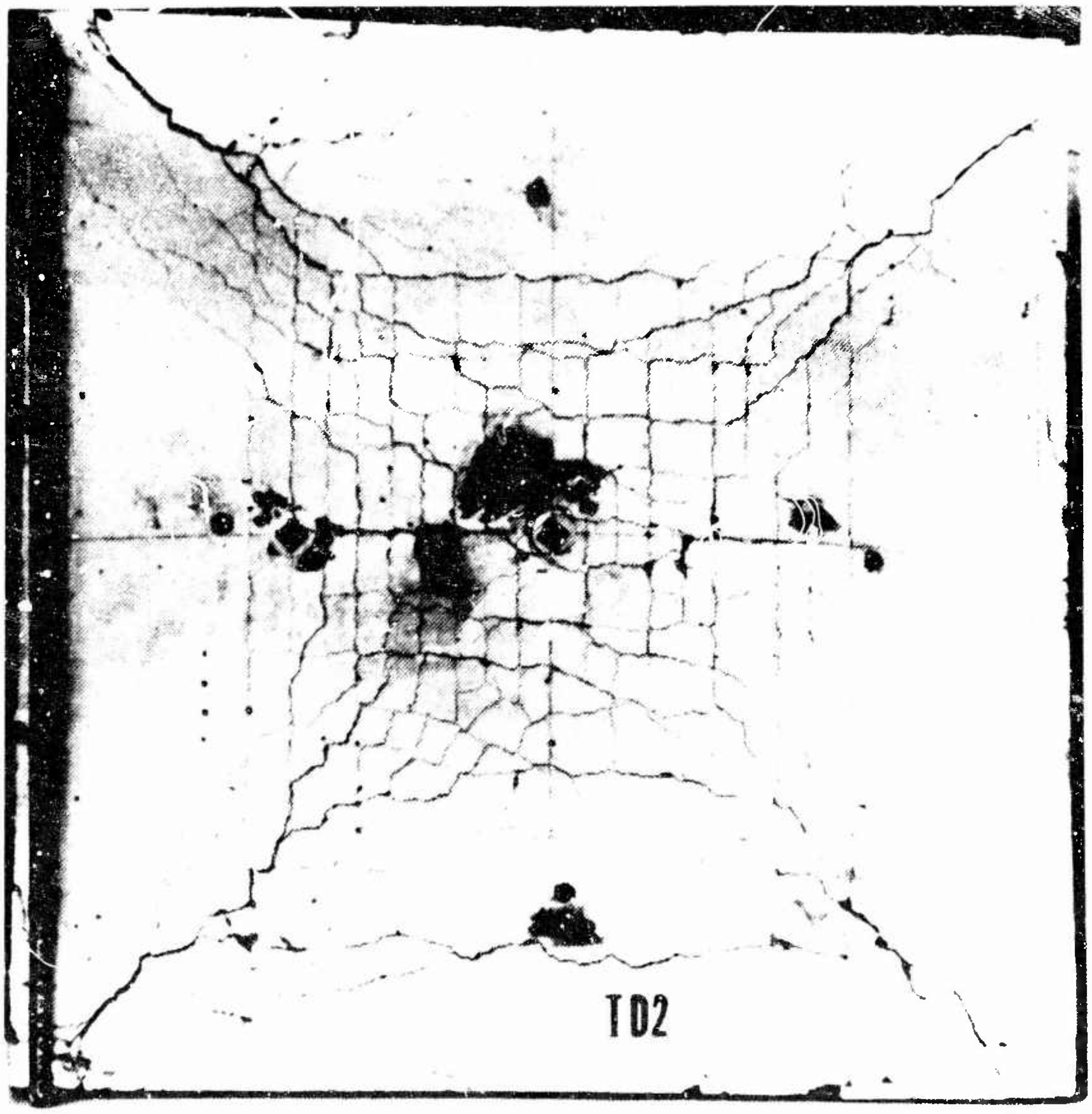


Figure 26 TENSION SURFACE OF R/C SLAB WITH 0.78 PERCENT STEEL SUBJECTED TO 9.0 PSI OVERPRESSURE

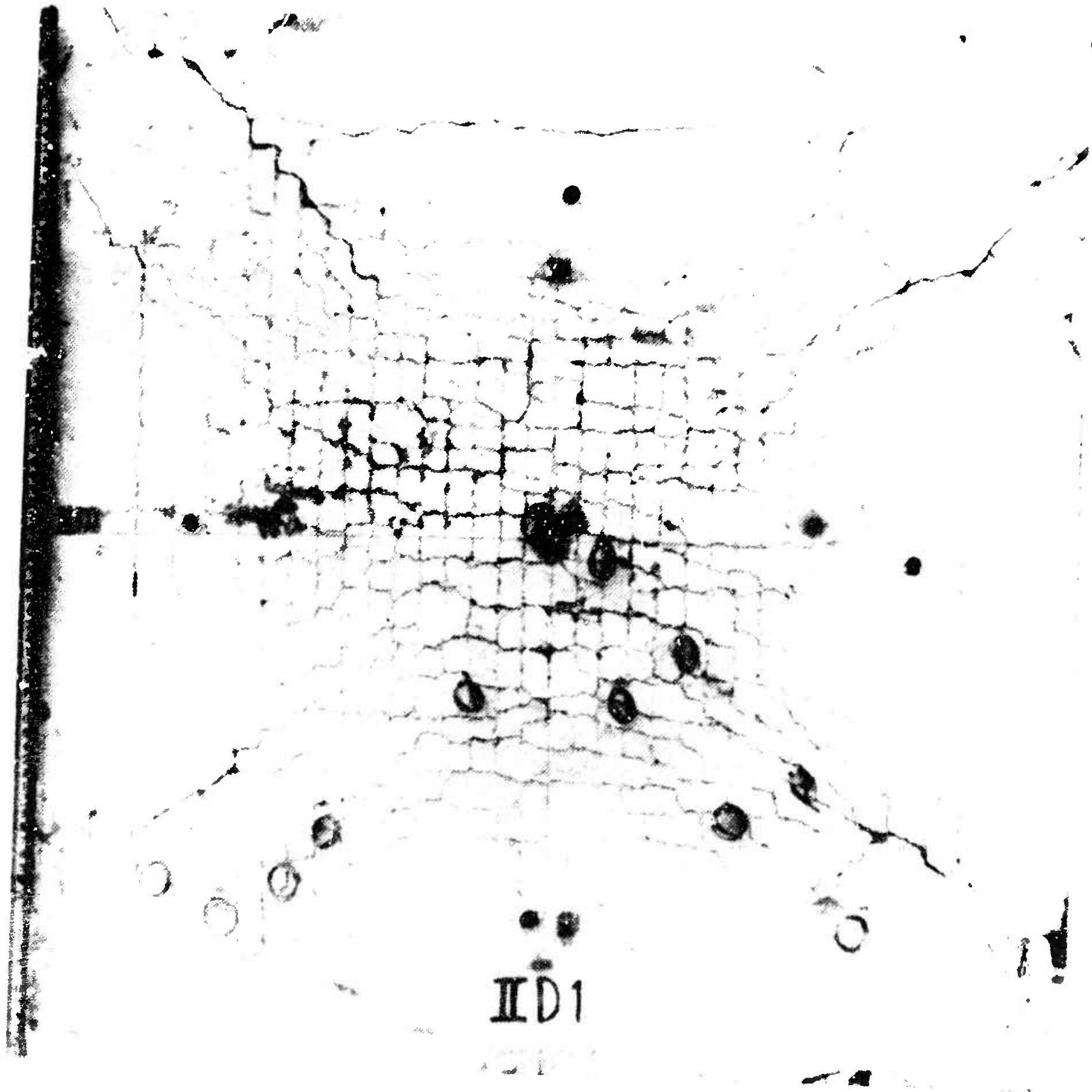


Figure 27 TENSION SURFACE OF R/C SLAB WITH 1.0 PERCENT STEEL SUBJECTED TO 12.5 PSI OVERPRESSURE

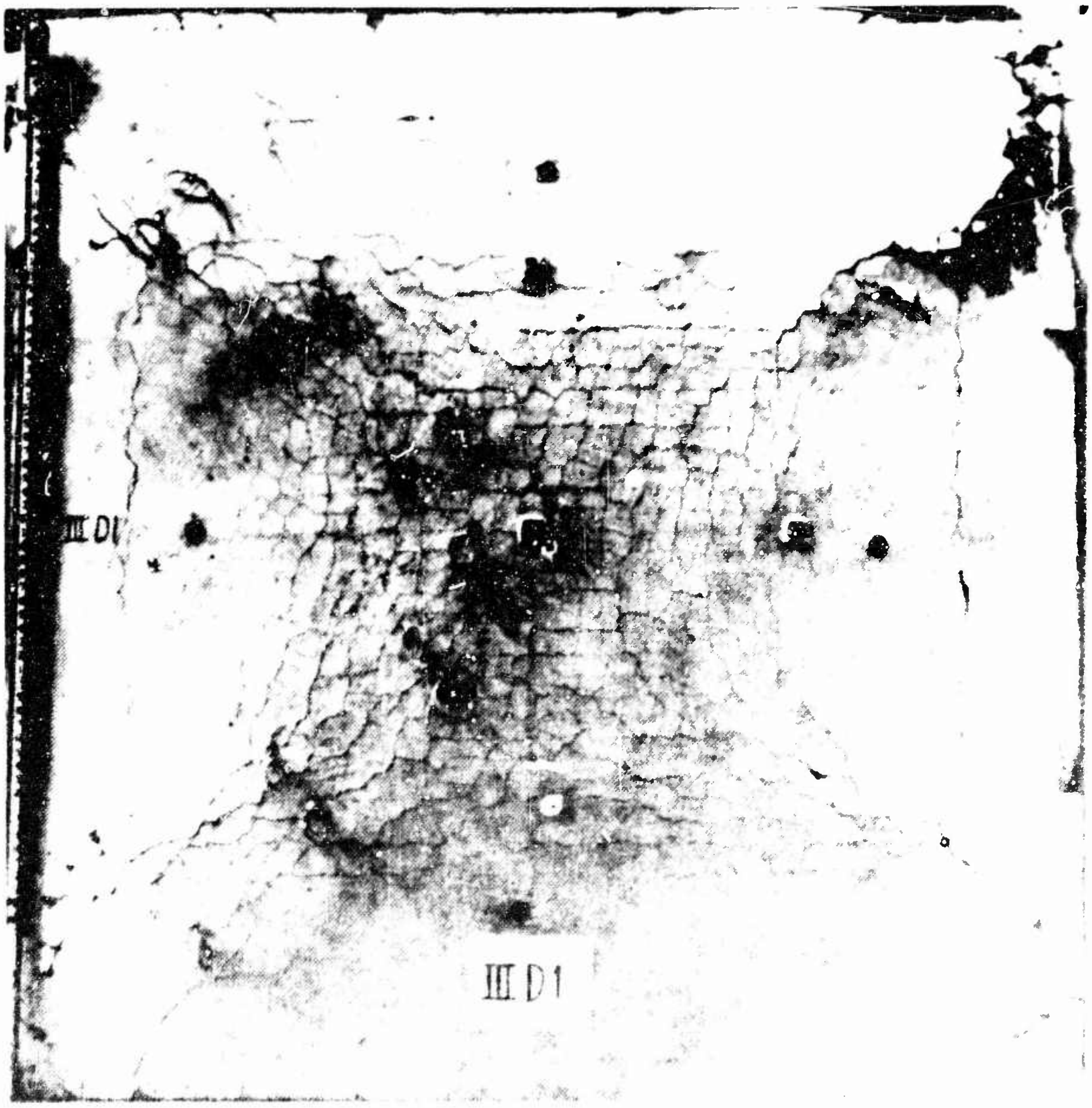


Figure 28 TENSION SURFACE OF R/C SLAB WITH 1.17 PERCENT STEEL SUBJECTED TO 13.2 PSI OVERPRESSURE

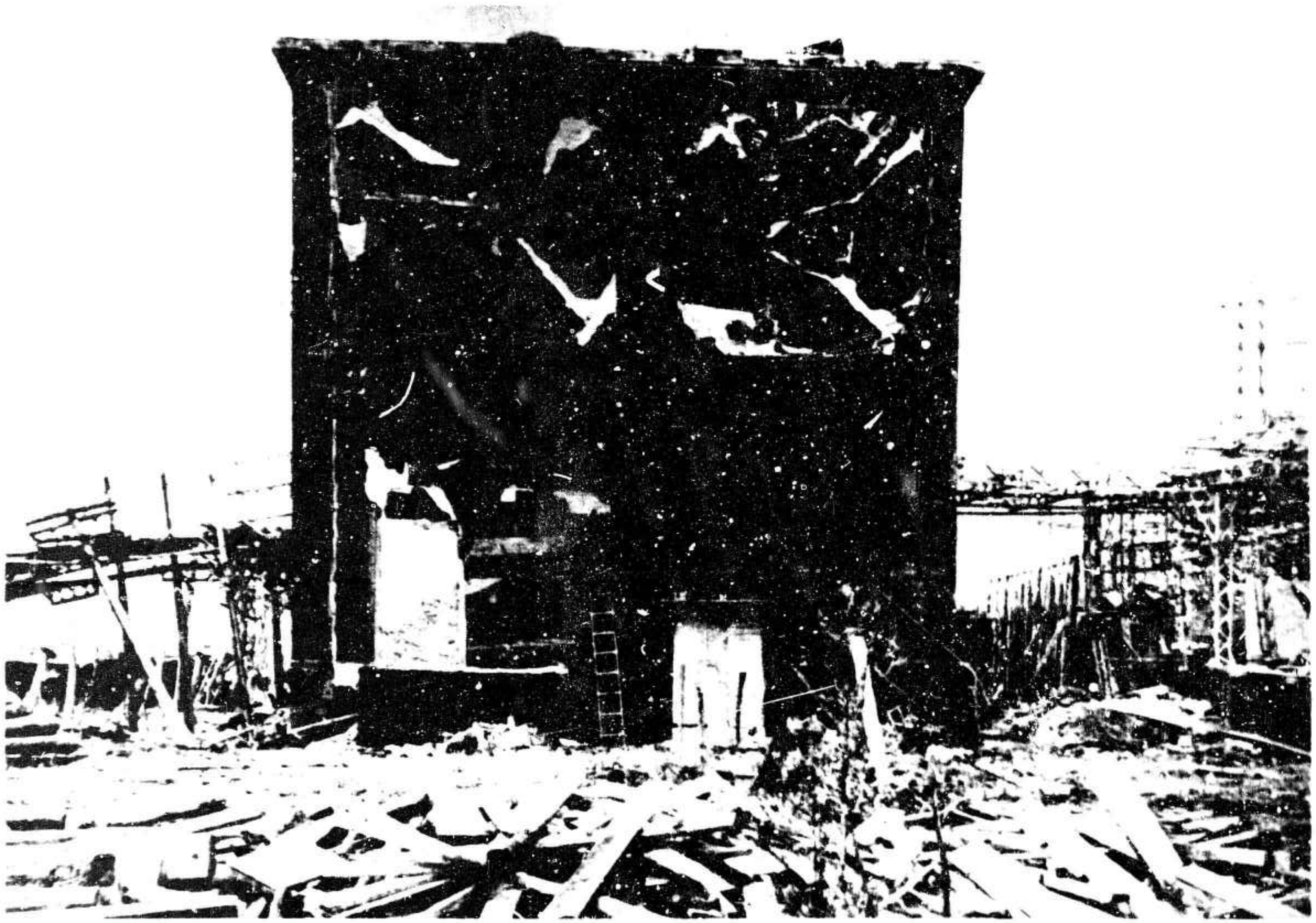


Figure 29 REINFORCED CONCRETE FRAME BUILDING SHOWING CRUSHED CONCRETE PANEL WALLS ON SIDE FACING EXPLOSION (0.68 MI FROM GROUND ZERO AT NAGASAKI)

Title: Blast Effects of Atomic Weapons Upon Curtain Walls and Partitions of Masonry and Other Materials

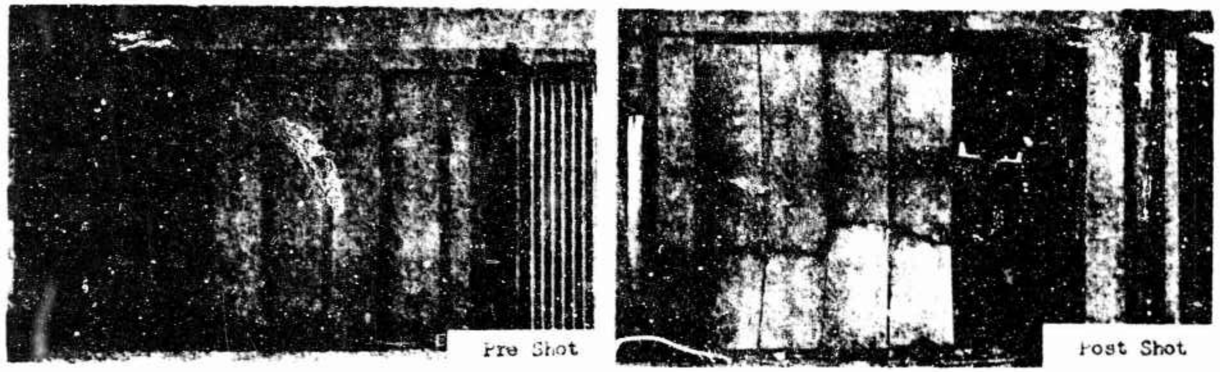
Author: Taylor, Benjamin C.

Source: Operation Upshot-Knothole, WT-741, DDC No. AD-636 766

Date: August 1956

Conclusion: Simply supported R/C slabs may undergo such large deflections under blast loading that they are pulled off their supports.

Remark: A rear wall consisting of precast R/C channel slabs was tested at the 7.5 psi overpressure range. Due to construction details, these slabs may be considered to have been simply supported along the top and bottom edges. Figure 30 reveals the extent of the damage sustained by this wall panel. All of the channel slabs were damaged with the maximum severity occurring in the center of the wall panel. The photograph of the interior of the test cell reveals that the flange reinforcing bars were separated from the channel slabs and that the permanent maximum deflections were considerable. This allowed some of the slabs to pull off their supports.



Note: The front wall was not tested.

c) Postshot,
Interior

Figure 30 PRESHOT AND POSTSHOT PHOTOGRAPHS OF PRECAST R/C CHANNEL SLAB REAR WALL AT 7.5 PSI OVERPRESSURE RANGE

Title: A Dynamic Ultimate Strength Study of Simply Supported Two-Way Reinforced Concrete Slabs

Author: Denton, D. R.

Source: U. S. Army Engineer Waterways Experiment Station Final Report, Contract OCD-PS-65-44, Office of Civil Defense

Date: April 1967

Conclusion: In the case of simply supported R/C slabs, excessive deformations may cause the entire slab to be pulled off its supports.

Remark: The simply supported R/C slab shown in Figure 31 has apparently pulled off its support along almost one entire edge. The permanent midpoint deflection for this slab was determined to be 17 in. while the corresponding deflection for all the other slabs tested in the subject reference ranges from 2.0 to 8.8 in.

Title: The Effects of Nuclear Weapons

Editor: Glasstone, Samuel

Source: U. S. Department of Defense, U. S. Atomic Energy Commission

Date: February 1964

Conclusion: Reinforced concrete members, if they are simply supported, may fail by undergoing such large deflections that they fall off their supports.

Remark: The R/C bridge with T-beam deck, shown in Figure 32, was located 0.44 mile from ground zero at Nagasaki. One span, 35 ft long, has been pulled off its supports and has fallen into the river.

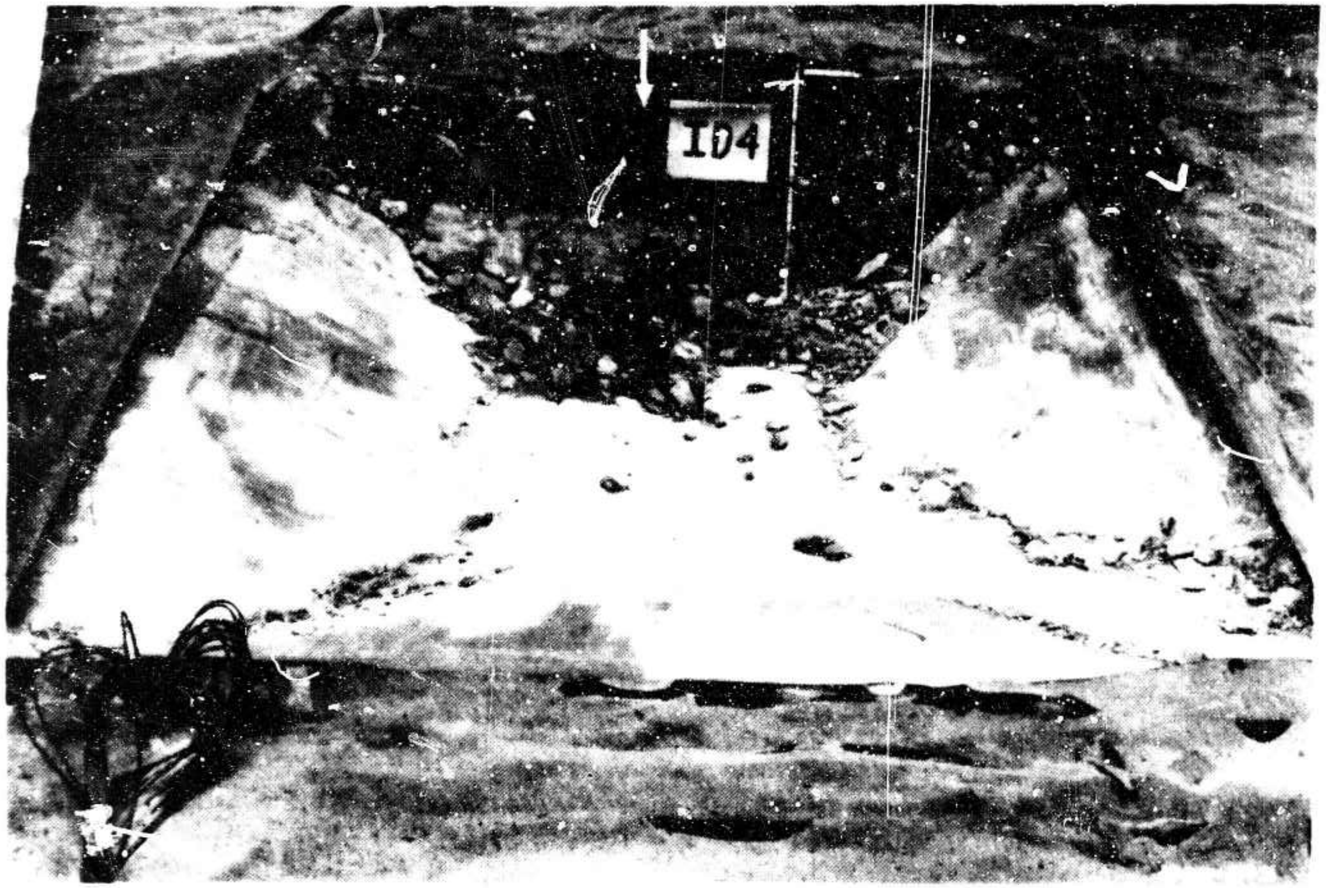


Figure 31 COMPRESSION SURFACE OF R/C SLAB WITH 0.78 PERCENT STEEL SUBJECTED TO 11.0 PSI OVERPRESSURE

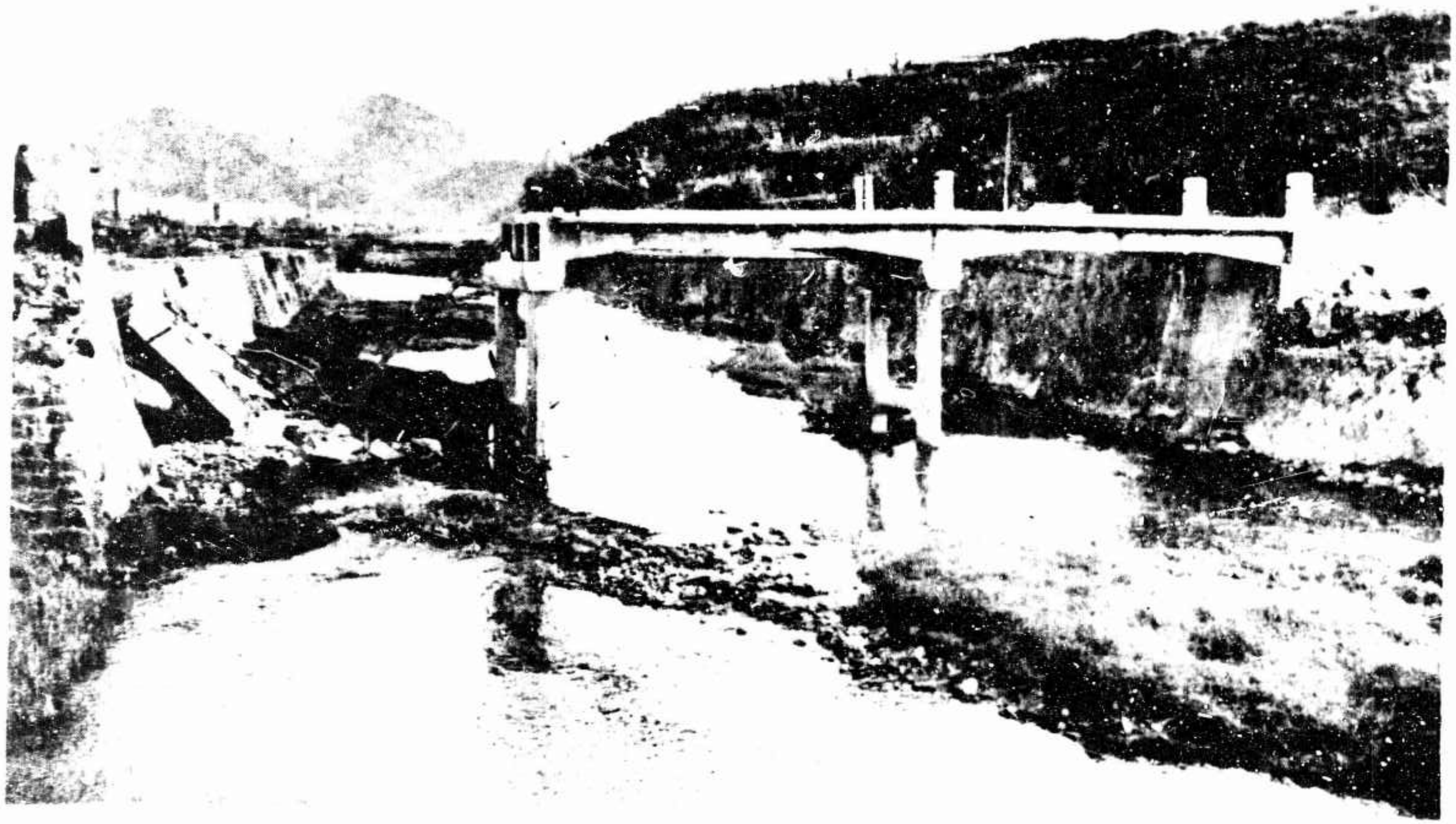


Figure 32 REINFORCED CONCRETE BRIDGE WITH T-BEAM DECK 0.44 MI FROM GROUND ZERO AT NAGASAKI

C. Secondary Fragments

Reinforced concrete bending members undergo an enormous amount of cracking in reaching their ultimate resistance. These cracks arise from bending, membrane, and splitting action and at high pressures they may be caused by tensile stress waves. When slab tests are carried to extreme deflections, the splitting response becomes fully developed and it superimposes a regular pattern of cracks on others that may exist. This pattern provides an upper bound on the size of secondary fragments. The splitting cracks will be found to follow the layout of the reinforcement.

Referring to Figure 33 from Ref. 4, we find three modes of splitting failure in beams. Only the modes shown in Figures 33b and 33c are appropriate for the slab. The failures shown in Figures 33b and 33d correspond to a wide bar spacing and those in Figures 33c and 33e to a narrow spacing. Evidence will be submitted to show that these modes also appear in slabs, however, here, the concrete cover is more difficult to strip off from the steel. The effect of splices in the reinforcement is clearly shown in Figure 34 where the stress discontinuity at the ends of the bars cause flexural and splitting cracks to occur. We anticipate similar effects in slabs with discontinuous reinforcement.

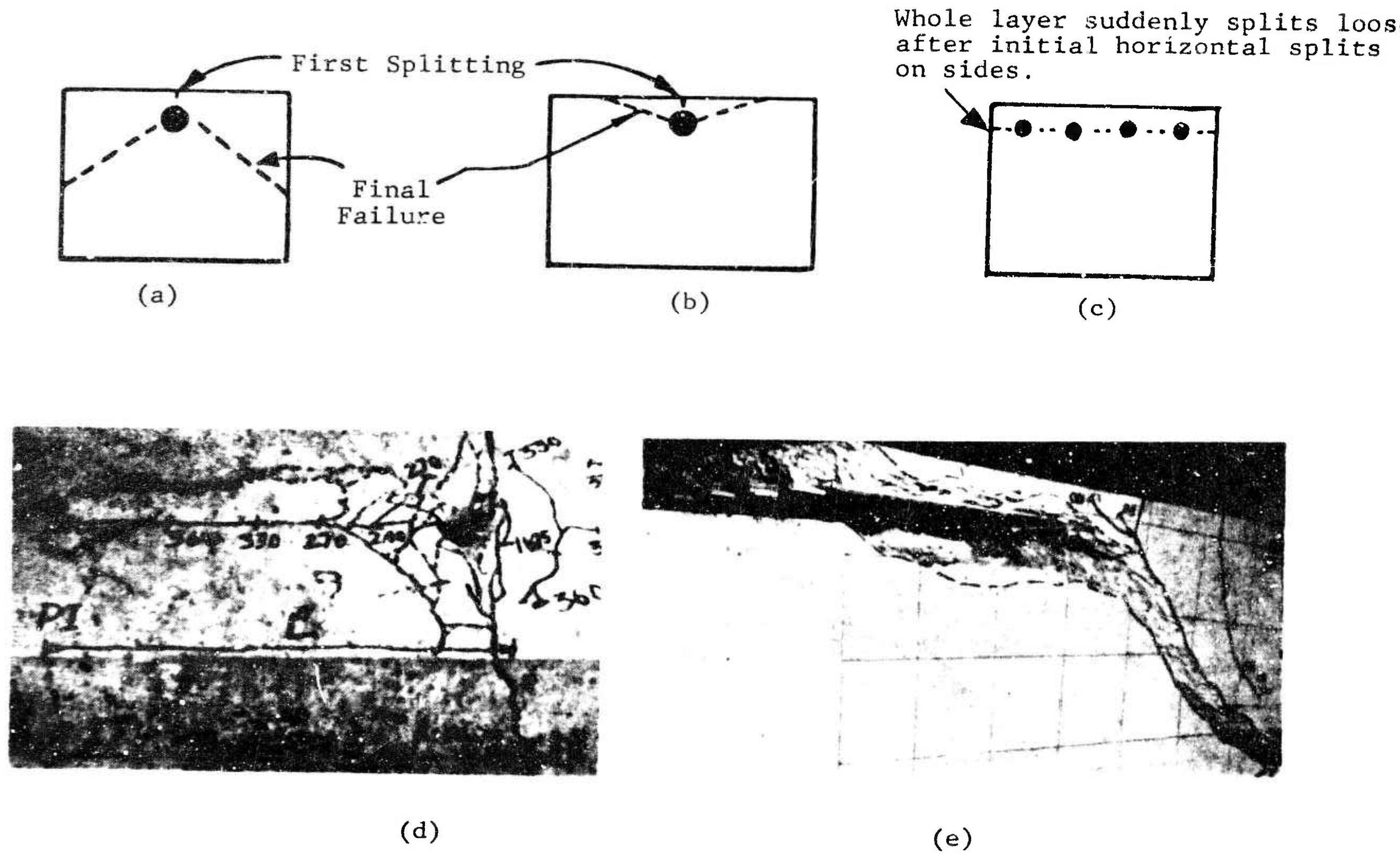
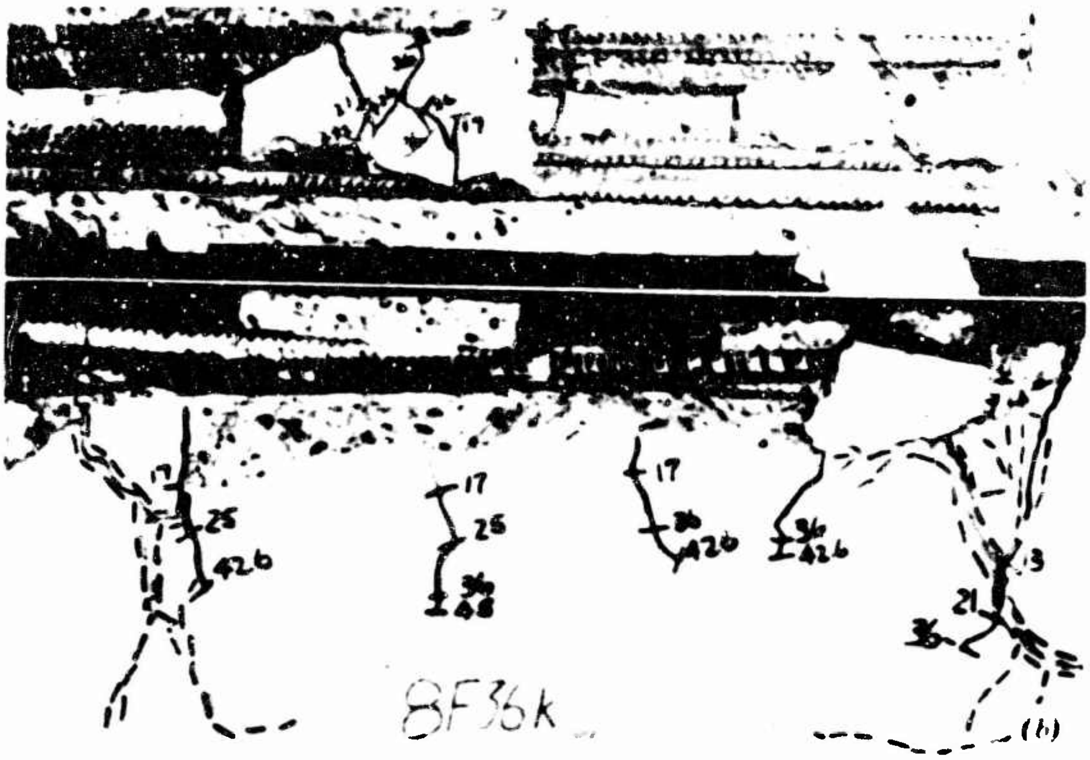
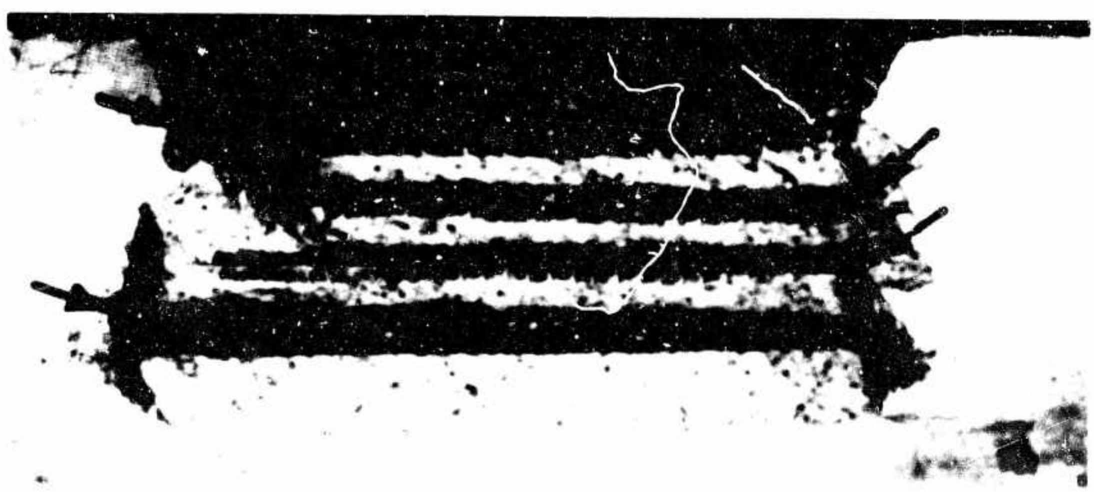


Figure 33 SPLITTING CRACKS AND ULTIMATE FAILURE. (a) TYPICAL, (b) AND (d) VERY WIDE BEAM, (c) AND (e) WITH CLOSELY SPACED BARS



(a)



(b)

Figure 34 SPLICE FAILURES. (a) VIOLENT FAILURE OF NO.8 BARS LAPPED 36 DIAM, (b) SHORTER SPLICE WITH CRACKED CONCRETE REMOVED TO SHOW SPLITTING SURFACE. ARROWS MARK END SLIPS OF BARS

Title: A Dynamic Ultimate Strength Study of Simply Supported Two-Way Reinforced Concrete Slabs

Author: Denton, D. R.

Source: U. S. Army Engineer Waterways Experiment Station Final Report, Contract OCD-PS-65-44, Office of Civil Defense

Date: April 1967

Conclusion: The crack patterns produced in the tension surfaces of R/C slabs under dynamic loading tend to follow the reinforcement layout. This tendency is greater for the smaller steel percentages.

Remarks: As shown in Figure 35, the crack patterns produced in the tension surface of R/C slabs under uniform static loading appear to be curvilinear and not to follow the rectangular reinforcement pattern. However, as observed in Figure 36, the pattern produced in a slab, with 0.78 percent steel, subjected to dynamic loading almost perfectly coincides with the reinforcement pattern in the central region of the slab. By way of contrast, the pattern produced in a slab with 1.17 percent steel under the same loading, Figure 37, is not nearly as perfect. It is our contention that the splitting action of the bars becomes more dominant at the larger deflections associated with the lower steel percentages.

Figure 35 TENSION SURFACE OF R/C SLAB WITH 1.0 PERCENT STEEL SUBJECTED TO 9.4 PSI UNIFORM STATIC LOADING

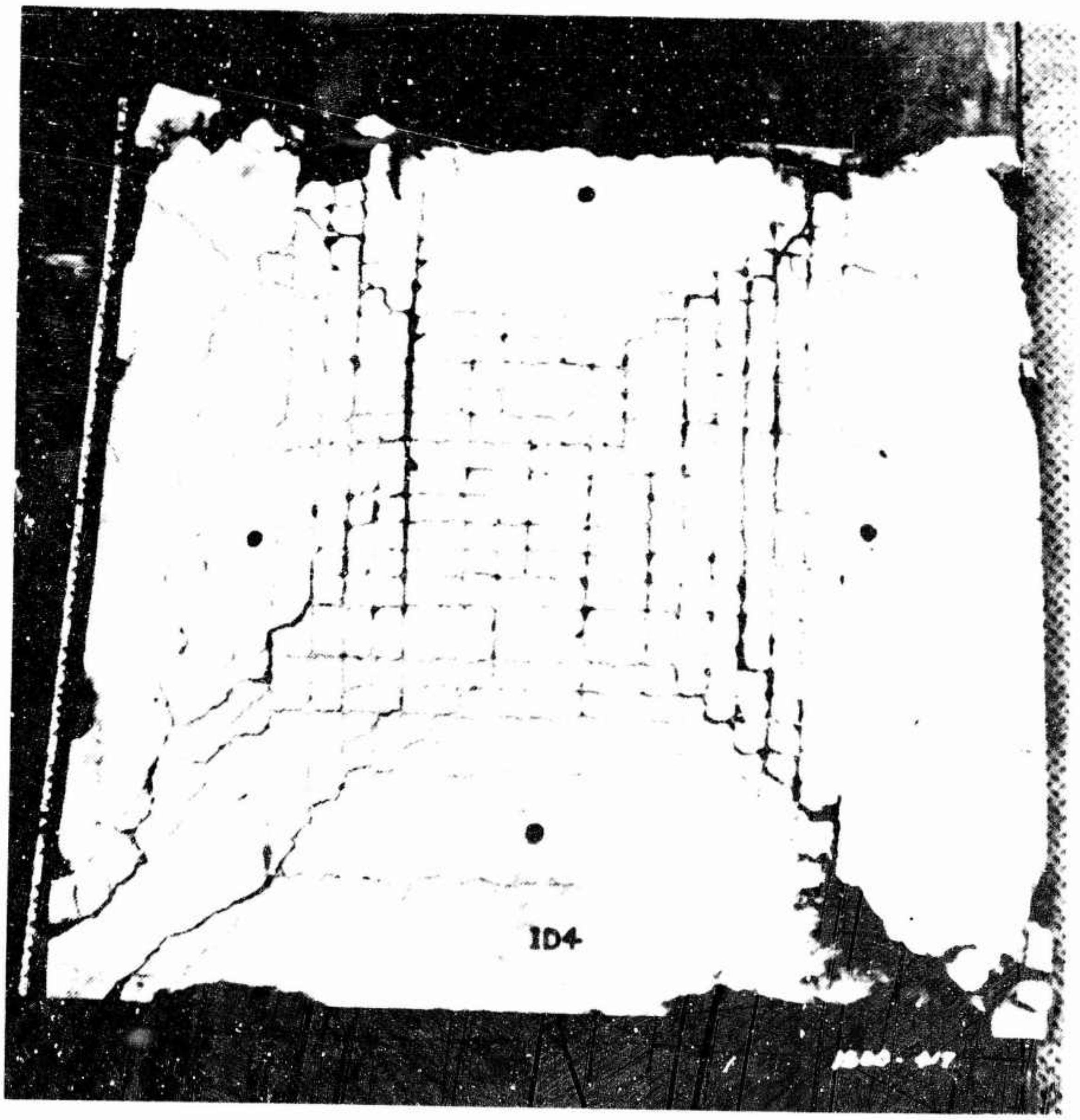


Figure 36 TENSION SURFACE OF R/C SLAB WITH 0.78 PERCENT STEEL SUBJECTED TO 11.0 PSI OVERPRESSURE

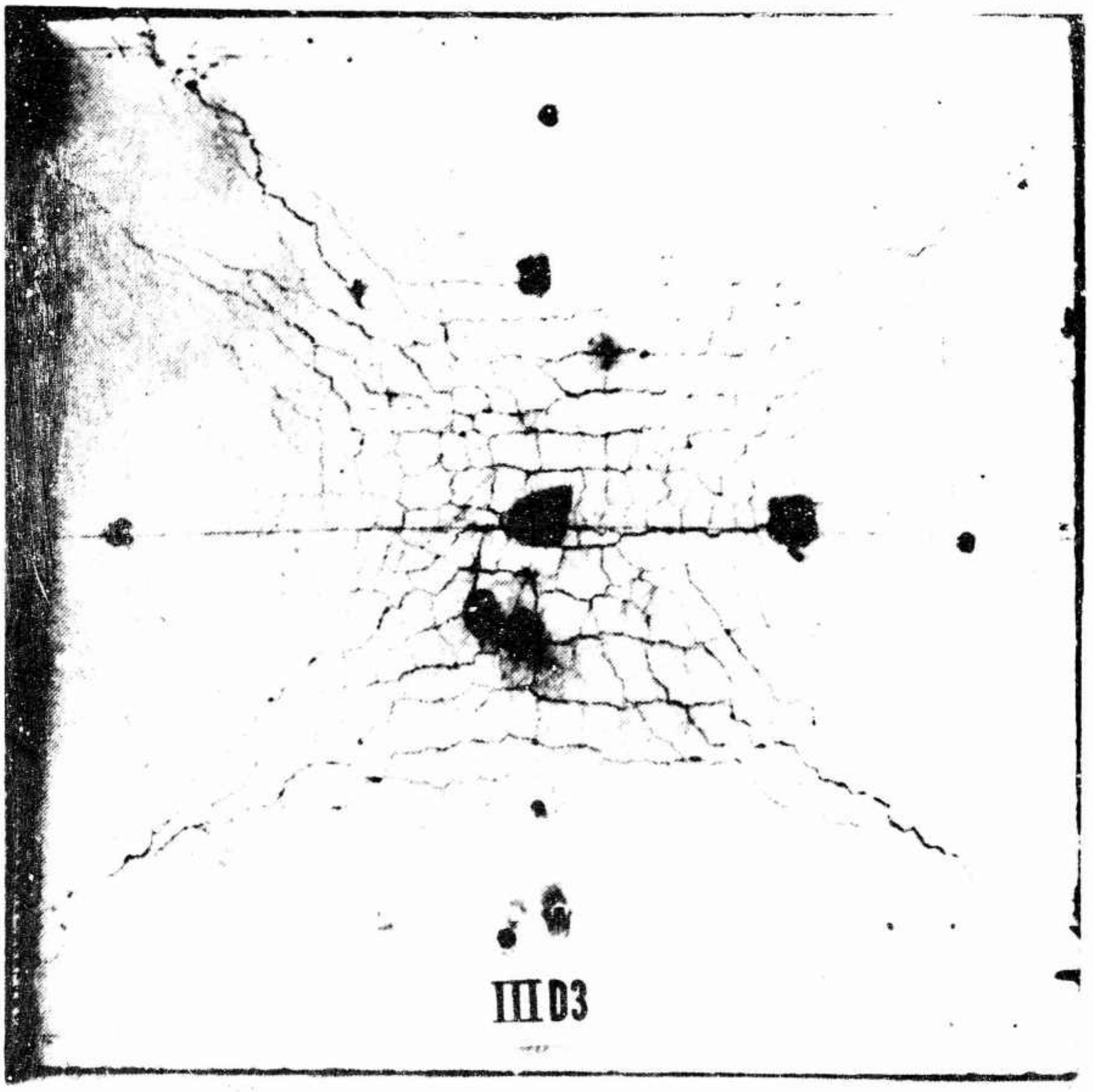


Figure 37 TENSION SURFACE OF R/C SLAB WITH 1.17 PERCENT STEEL SUBJECTED TO 11.0 PSI OVERPRESSURE

Title: Resistance and Behavior of Concrete Slabs Under Static and Dynamic Uniform Loading with Edges Clamped and Laterally Restrained

Author: Keenan, W. A.

Source: Technical Report, Naval Civil Engineering Laboratory Port Hueneme, California

Date: To be published in 1968

Conclusion: Secondary concrete fragments originate from the downstream face of a R/C slab and are confined to the layer of concrete covering the steel. Their maximum size is bounded by the dimensions of the reinforcing grid.

Remark: A series of R/C slabs were tested under dynamic pressures of up to 120 psi. Extensive crack patterns developed in these slabs which were similar to that shown in Figure 23; they tend to follow the outline of the reinforcing layout. It was observed from these tests that secondary fragments came from the layer of concrete cover on the downstream slab face. Concrete stripped from this layer exposed the steel. All of the concrete above the downstream reinforcement remained intact. Furthermore, the largest fragment observed had the dimensions of the reinforcing grid; most of them are smaller.

We estimate that about 30 percent of the concrete cover is stripped away at the 100 psi level. Since the ACI code calls for a minimum cover of 3/4 in. a 20 ft by 10 ft panel would produce about 563 lb of secondary fragments. If the reinforcement is laid out in a 6 in. by 6 in. grid, the fragments will weigh less than 2.35 lb each.

Title: A Dynamic Ultimate Strength Study of Simply Supported Two-Way Reinforced Concrete Slabs

Author: Denton, D. R.

Source: U. S. Army Engineer Waterways Experiment Station Final Report, Contract OCD-PS-65-44, Office of Civil Defense

Date: April 1967

Conclusion: Compressive chipping will produce some secondary fragments from R/C slabs.

Remark: Typical concrete compression failures are observed along the diagonals near the corners of the R/C slab shown in Figure 38. A detailed view of one of the corners of this slab is shown in Figure 39. It is interesting to observe that the secondary fragments which were produced tended to remain w[illegible] the slab on the upstream face.

Title: Behavior of Metals Under Impulsive Loads

Authors: Rinehart, John S. and Pearson, John

Source: Dover Publications, Inc., New York

Date: 1954

Conclusion: When the peak dynamic overpressure is less than the tensile strength of concrete (about 300 psi), no secondary fragments will be produced by scabbing.

Remark: The complex phenomenon of scabbing is dependent upon the detailed understanding of the interaction of stress waves as they reflect from the various boundaries of an object.

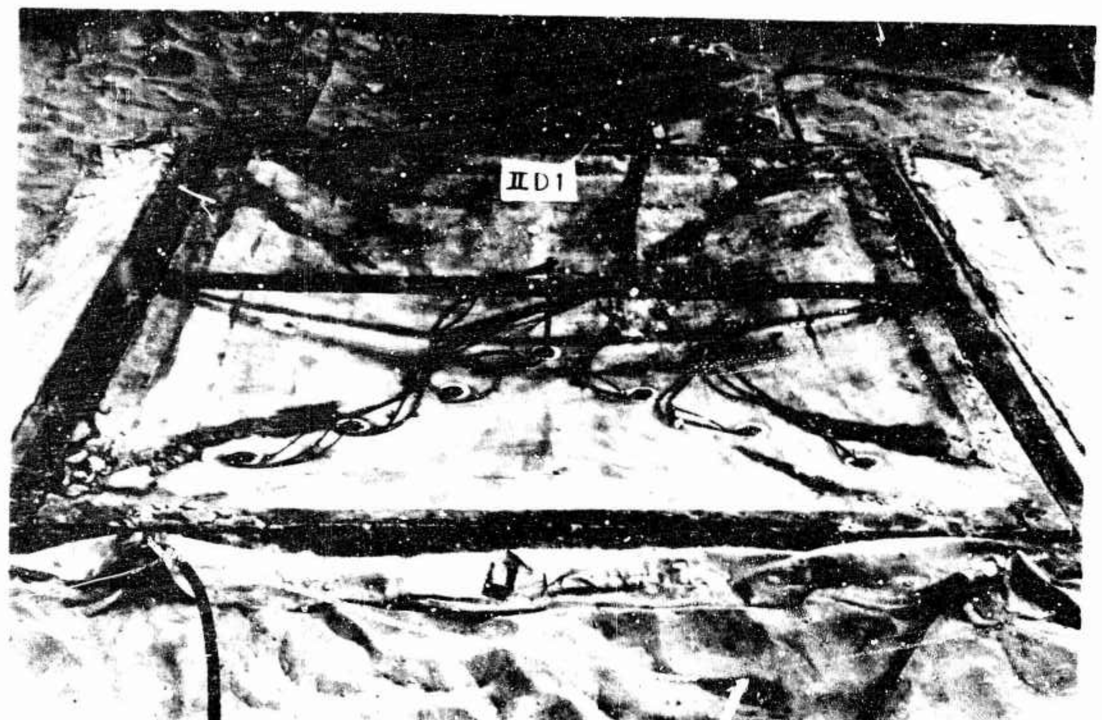


Figure 38 COMPRESSION SURFACE OF R/C SLAB WITH 1.0 PERCENT STEEL SUBJECTED TO 12.5 PSI OVERPRESSURE

Figure 39 COMPRESSION CHIPPING PRODUCED IN R/C SLAB WITH 1.0 PERCENT STEEL SUBJECTED TO 12.5 PSI OVERPRESSURE

A typical example of a scabbing type of fracture is illustrated in Figure 40. Basically the two most important factors influencing scabbing are: (1) the magnitude of the tensile stress wave with respect to the magnitude of the fracture strength of the material, and (2) the shape of the stress wave. If the magnitude of the tensile stress wave is less than the strength of the material, no scabbing will occur. The present program is concerned with pressure levels below 100 psi. Here, the low level stress waves will help shake stubborn secondary fragments loose from the slab.

Figure 40 CROSS SECTION OF MILD STEEL PLATE SHOWING MULTIPLE SCABBING

CHAPTER V
DISCUSSION OF RESULTS

The occurrence of primary fragmentation is the final stage in the response of a R/C slab. Before this behavior is realized, enormous damage is entertained by the slab and certainly its usefulness has long been exhausted. Studies of R/C members for conventional applications terminate when either the maximum resistance is obtained or when cracks become unacceptably large. Even in protective construction, interest is not sustained as far as the fragmentation stage. In view of this situation it is not surprising that most investigations of R/C slabs are not relevant to the fragmentation problem.

The formation of a primary fragment requires that the reinforcing steel around its periphery be fractured. With this in mind, the current study concentrated on situations which might lead to fracture or which displayed fracture of the reinforcement. The difficulty and infrequency of encountering this response has contributed most significantly to our conclusion that R/C slabs do not develop primary fragments.

We can expand our insight into the fragmentation problem by backing up a little and examining the crack patterns which are formed in dynamically loaded slabs. Taking a much more subjective approach than that used in the case studies, we can identify three basic causes of concrete cracking; bending, tensile membrane action, and wedging action of the reinforcing steel. Our motivation for studying these concrete cracks stems from the observation that the steel stress is greatest at the cracks (Ref. 4) and, consequently, if steel fracture occurs it will do so at such locations.

Beginning with the unreinforced masonry wall described in Case 6, we find a strong diagonal crack development which terminates in a rectangular crack in the center of the slab. This pattern is typical of those obtained in studies of monolithic frangible slabs subjected to uniform dynamic pressures (Ref. 13 and 14). This remarkable pattern is caused by bending stresses at small deflections. We note that fracture does not occur at the center of the slab where the stresses are the greatest. A statistical explanation has been suggested to describe this behavior. The arguments employed point out that the high stresses at the center of the slab involve only a small volume of material and, hence, there is a small likelihood of finding a critical flaw. At the other extreme, the border of the slab provides a large volume in which a critical flaw may occur with high frequency; but, here the stresses are quite low. Between these extremes we find a combination of applied stress and flaw likelihood which maximizes the fracture probability; namely, the rectangular crack pattern.

The addition of steel reinforcement to masonry panels does not affect the elastic bending crack pattern; however, it does retard its onset. More important, it provides a panel with an elastic-plastic type moment/curvature relationship. This enables the panel to develop yield lines along which severe cracking will take place. Plastic collapse modes are found in several of the case studies dealing with R/C slabs.

The classic static collapse mode for square isotropic slabs is an X pattern which is formed by yield lines along the diagonals. As pointed out in Case 9, this pattern was obtained in both full scale and 1/24 scale dynamic panel tests. The Nagasaki experience provides several examples of yield line development. In Case 5 we find plastic hinges in beam elements, in addition to a well developed slab yield line. A perfect static yield pattern is illustrated in Case 14 for a fixed edge slab, i.e., yield lines form around the border and along the diagonals.

The work of Denton, Case 13, illustrates the similarity between the static and dynamic crack patterns in slabs with nonhomogeneous reinforcement. In all cases, the corners of the slabs have been reinforced more heavily than the central region. Furthermore, bends in alternate bars were made near the edges (1 to 2 ft from the edges) to provide both tension and compression steel in the boundary regions. These bends produced the large cracks shown in Figures 25 through 28 which parallel the slab edges. Such cracks do not arise in slabs with homogeneous reinforcement, and except for their presence, the principal crack pattern is very close to the classic X mode.

Elastic bending failures characteristically lead to cracks which do not penetrate the entire slab thickness. In plastic bending the rotations which concentrate at the yield lines may lead to cracks which completely penetrate the slab. These cracks arise from tensile bending stresses acting over most of the slab section and from compressive shear failure of the remaining compression layer. In both the elastic and plastic cases, subsequent tensile membrane action of the slab will cause partial cracks to pass through the entire slab thickness and will tend to increase the width of all cracks. Such membrane action becomes significant at deflections of the order of the slab thickness.

To complete our account of cracking we recall that a wedging action is associated with the "pull out" motion of a deformed reinforcing bar. Where the steel stress is sufficiently high, this action manifests itself in a surface crack which occurs in the slab face directly above the reinforcing bars. Such cracking is discussed in Case 18 and the resulting crack pattern is clearly illustrated in Figures 27 and 36. This effect was also exhibited in Keevan's Study which is described in Case 10.

The influence of tensile membrane stresses in severely loaded slabs is very pronounced and would be quite sufficient to cause tension cracks which would sever the slab section. However, the slab is so extensively cracked by other phenomena before the membrane behavior dominates the stress pattern that membrane action is largely confined to the extension and separation of existing cracks such as those caused by wedging action. As we see in Case 10, the membrane tension can completely isolate small islands of concrete with the result that the pressure loads easily pass through the slab to reduce the net transverse forces acting on the various regions of the slab.

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